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FOREWORD

As national energy policies and strategy now begin to take shape and breathe life, there appears to be no lessening of the arguments and debate between proponents of energy conservation, on the one hand, and advocates of increased domestic oil and gas production, on the other. Similarly, the debates continue to rage between supporters of new exploration for fossil energy resources and the sometimes unyielding stances on environmental disturbances and protection. In the midst of this crescendo, one can now begin to hear the rising sounds of cooler and, it is hoped, compromising heads who recognize one inescapable fact: if our Nation is to avoid critical dependence on foreign and sometimes hostile sources to satisfy our seemingly insatiable appetite for energy, we must adopt a posture that reflects a balance between increased conservation and increased production, still assuring environmental responsibility as it affects our future.

Accomplishing this objective is no small task. But the arguments must cease if we are to succeed. And we must embrace an approach which guarantees that: (1) today's research programs accurately reflect tomorrow's needs and priorities, and (2) more importantly, those programs provide a technologically achievable pathway that enables us to meet the needs and priorities of the next several decades. Developing sound research strategies, securing adequate research funding, and skillfully integrating federally funded programs with private sector needs are all part of this approach.

Another vital component of our future energy scenario is the successful transfer of technology and commercialization of products and processes developed under federally funded programs. The Department of Energy's recent re-molding of its planned oil and gas research program from one that emphasizes long-term research to one that achieves a balance between near-term, mid-term, and long-term objectives is a giant step in the direction of increased technology transfer. But care must also be taken that higher levels of funding for commercialization of technology not be at the sole expense of fundamental research efforts needed to advance technology and guarantee a supply of additional transfer opportunities in the future. Similarly, we must not impact science education and university programs of energy research. Such programs are not only critical to development of future technologies; they also provide the necessary R&D efforts used to produce the well-trained professional staff so critical to viable future programs in both the private and public sectors.

There is no better example of successful research and technology transfer programs than that of the National Institute for Petroleum and Energy Research (NIPER). The cooperative efforts of both DOE and IITRI/NIPER staff combine to create a careful crafting of strategies and approaches in a research program and environment that is not only compatible with private sector needs, but which actually encourages their interest and participation in research activities at the NIPER facility.

Research programs at NIPER cover a wide spectrum of specific technical tasks, all of which relate to three broad technology areas: (1) Enhanced oil recovery and all of the associated technical activities such as reservoir characterization and imaging techniques; (2) Alternative fuels evaluation and testing, including the supporting technologies of thermodynamics research and fuels characterization; (3) Environmental technology related to production, transportation, and utilization of oil and gas. These three program areas directly relate to the three issues of critical importance to our Nation's energy future, energy conservation, energy supply, and environmental protection. Success in achieving the right balance between these issues will depend on how well we as a Nation evaluate alternatives through appropriately structured research and development programs. Achieving the right balance will also depend on our faith in technology and its many uses, and our willingness to put it to the test. Most people accept that technology has done far more <u>for</u> us than <u>to</u> us. In today's world, technology is often its own cure, producing real solutions to real problems and, in the process, reconciling seemingly conflicting goals. NIPER will continue to do its part in providing those solutions.

James M. Deterding

James M. Deterding
Director, NIPER

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I. EXECUTIVE SUMMARY

Fiscal year 1990 completes NIPER's seventh successful year of research for the Department of Energy and represents a year beginning transition from the long-term, high-risk program established in 1983 to the highly targeted near-term research program outlined in DOE's National Energy Strategy—Advanced Oil Recovery Program (NES-AORP) issued April 1990 by the Assistant Secretary of Fossil Energy, Deputy Assistant Secretary for Oil, Gas, Shale and Special Technologies. The prime objective of the Advanced Oil Recovery Program Implementation Plan (AORPIP) is to maximize the economic producibility of the domestic oil resource.

Under a cooperative agreement established in 1983 between the DOE and IIT Research Institute (IITRI), NIPER has a substantial commitment to support the AORPIP through a DOE-funded Base Program research and technology development effort; to provide problem-solving technical assistance to DOE and other government agencies through a Supplemental Government Program (SGP); and to support the research needs of industrial clients through a Work for Others (WFO) Program.

In FY90, IITRI/NIPER was responsible for 14 Base Program projects with total DOE funding of over 4.6 million dollars. Eleven projects received funding under the Office of Fossil Energy's (FE) EOR Heavy and EOR Light Oil Programs and three under FE's Advanced Extraction and Process Technology (AEPT) Program. AEPT has responsibility for advanced research instrumentation and cross-cutting fundamental and exploratory research relating to the evaluation, extraction, processing, and upgrading of oil, gas, shale oil, tar sands, and underground coal gasification resources. The Energy Production Research (EPR) Department conducted research on 12 projects; four each under the categories of Geotechnology, Chemical and Microbial EOR, and Thermal and Gas EOR. The Fuels Research (FR) Department managed one project in the category of Processing and Thermodynamics and one in Fuel Chemistry. The FR Department also manages a Fuels/Engines Section, but no Base Program work is currently performed in this area. Engines work is important to NIPER's total program, however, as it provides information on the changes and overall acceptability of today's transportation fuels and represents an area of rapid growth.

The Base Program research effort continues to provide continuity and stability to the oil and gas research program which began at the Bartlesville Center over 70 years ago. Although some Base Program projects continue long-term investigations of difficult and complex problems involved in recovering a larger portion of the estimated 300 million barrels of oil remaining in domestic reservoirs, others have advanced markedly and are now providing problem-solving research support to NIPER's clients through technology transfer. In FY90, 35 SGP projects and 71 WFO projects were active with total funding of over 6 million dollars. The research volume of the SGP Program, initiated in 1988, has grown at an average annual rate of 21%, and industrial volume in the WFO Program has grown at a phenomenal average annual rate of over 95% since its inception in the latter part of 1983. This rapid growth confirms the genuine need of other government agencies and industry for NIPER's capabilities and expertise in technology development and problem-solving research. The titles of the SGP and WFO projects that were active during FY90 are listed in appendices A and B. They denote the relationship between the Base Program and research being performed for other government agencies and industry.

The Base Program provides supporting research in most areas outlined in the AORPIP which include: (1) reservoir description methods, tools, instrumentation, and modeling, (2) extraction techniques for secondary and tertiary recovery, (3) petroleum chemistry/processing covering constraints on production and refining problems, and (4) technology transfer. A fifth area, the environment, was not a part of Base Program research during FY90, but expertise developed under previous projects provides environmental support to the DOE and other government agencies under the SGP Program.

It is the purpose of this Annual Report to provide a summary of significant research findings of the work performed in categories 1 through 3 above. The fourth category, technology transfer, is continuously ongoing through technical publications and presentations; sponsoring and cosponsoring symposia, meetings, and conferences; participating in professional society and association activities; providing data base support and development to both DOE and industry; redesigning and improving reservoir simulators; cooperating with other oil-producing countries through training and DOE agreements; and working closely with independent oil producers. In FY90, the research staff published 56 reports, 37 of which were submitted to DOE as program deliverables. In addition, the staff presented 24 technical papers at different professional meetings, including the Seventh DOE/SPE Symposium on EOR in April 1990, where NIPER authors presented seven technical papers representing 5% of the total number of papers presented. These associated activities, along with interactions within the SGP and WFO Programs, place NIPER directly in touch with companies, universities, societies, and organizations involved in oil, gas, and fuels research and development. Furthermore, they provide the type of feedback essential for the identification of problematic areas needing additional research.

The overall research program is coordinated through the Bartlesville Project Office (BPO) which is collocated with NIPER and serves as the DOE administrator of the cooperative agreement. That office is delegated the lead assignment for implementing the Office of Fossil Energy's (FE) programs in Enhanced Oil Recovery (EOR) and Advanced Extraction and Process Technology (AEPT) and manages a number of projects executed by (1) NIPER, which utilizes the Federal equipment and facilities at Bartlesville; (2) industrial and research organizations; (3) universities; and (4) National Laboratories.

Late in FY90, NIPER received authorization to begin focusing a portion of its research on specific areas outlined in the AORPIP. As an example, tasks in the thermal recovery projects, originally somewhat generic in nature, were targeted towards improving oil recovery in DOE's Naval Petroleum Reserve (NPR) steamflood pilot tests at NPR No. 1, Elk Hills (CA) field and NPR No. 3, Teapot Dome (WY) field. Two short-term SGP projects were initiated: one to determine the general characteristics of Class 1 deltaic reservoirs, such as those having top priority for study under the AORPIP, and the other to determine the reserves, refining capabilities, and overall potential of heavy oil recovery in states where it has been only marginally successful.

ENERGY PRODUCTION RESEARCH

In FY90, the Energy Production Research (EPR) Department was responsible for 12 Base Program projects, 17 SGP projects, and 30 projects for clients in the WFO Program. Base Program research is being conducted in the areas of Geotechnology, Chemical and Microbial EOR, and Gas and Thermal EOR. The need for supporting research in these areas is well defined in the AORPIP. The FY90 research effort was constituted according to DOE's previous Program Plan for Enhanced Oil Recovery which encompassed a more generic approach to problem-solving research. The new implementation plan builds upon the earlier program but focuses the research on specific classes of reservoirs which have the greatest ultimate recovery potential but are approaching their economic production limits and could soon be abandoned. Late in the fiscal year, the DOE authorized several new SGP projects and changed the direction of some Base Program projects to provide immediate research and analytical support to the AORPIP.

Geotechnology

NIPER's Base Program projects in geotechnology provide for research in the areas of reservoir assessment and characterization, three-phase relative permeability measurements, and imaging applications for studying rock pore structures and the visualization of fluid distributions in porous media. In addition, analytical support is provided to DOE's Tertiary Oil Recovery Information System (TORIS) which plays a very important role in the AORPIP with respect to data management.

Reservoir Assessment and Characterization

It is stipulated in the AORPIP, and confirmed by industry, that understanding and quantifying reservoir heterogeneities through reservoir characterization is critical to economic EOR.

Since 1986, NIPER has been responsible for a major effort in reservoir characterization. The first reservoir characterized was the Muddy formation of Bell Creek (MT) field. From the resulting data collection, a geological/engineering model was developed in a format suitable for computer simulation. Later in the study, geological data from a tertiary incentive project (TIP) portion and surrounding area of Unit 'A' Bell Creek field were used to refine the model and evaluate, quantitatively, the influence of critical heterogeneities in the TIP area. During FY90, the modeling program was extended to the Almond formation of Patrick Draw (WY) field to determine the extent to which the architecture and behavior of shoreline barriers can be generalized meaningfully. Work on the Almond formation is to continue in FY91, incorporating a data base for shoreline barrier reservoirs which are in the top ten priority class of reservoirs outlined in the AORPIP.

To assist the DOE in implementing its new plan, an SGP project was approved late in FY90 to determine the general characteristics of Class 1, unstructured, fluvial-dominated deltaic reservoirs. These reservoirs have been selected as the top priority class for data analysis and problem definition. The objective of the SGP project is to identify the types of drilling strategy, completion, and production technologies applicable to these reservoirs.

Two other SGP projects were initiated late in FY90. One is to develop techniques for mapping the types and volumes of clays within a reservoir. The importance of this project was identified from earlier studies of Patrick Draw field where it was determined that reservoir clays could be a serious impediment to effective exploitation of the hydrocarbon resources and complicate wireline log determinations of hydrocarbons in place. The other SGP project is to study the use of isotopic techniques to detect fluid migration patterns into, within, and out of a reservoir by adapting natural isotopic geochemical methods to the requirements of quantitative hydrodynamic reservoir modeling. Lateral or vertical intercommunication through imperfectly sealed traps can be detected by geochemical, geopressure, and geothermal anomalies in a number of oil fields, and undesirable intercommunication can result in poor economics, due to loss of oil recovery injectants, and cause environmental problems if there should be intercommunication with freshwater aquifers.

NIPER has concluded a multiclient WFO project on reservoir characterization that was funded by three international oil companies. For this project, a quantitative geologic model was developed for the Shannon formation, Teapot Dome (WY) field, based on field descriptions of sedimentology and permeability and porosity distributions measured on more than 1,200 formation outcrop cores. The outcrop-based model developed was compared to data from the subsurface productive zone in both shallow and relatively deep reservoirs to determine the degree of similarity between the outcrop and reservoirs. The results of this study indicated: greater detail in simulator input is required when a reservoir is heterogeneous and the viscosity ratio between injected and formation fluids is adverse; failure to account for the distribution of discontinuous, high-permeability sand layers will result in an overly optimistic prediction of waterflood production; and the presence of small-scale heterogeneities will increase dispersivity of a water front, decrease the effective permeability, reduce fingering, and thus improve sweep efficiency and increase oil recovery.

Near the end of FY90, the DOE authorized IITRI/NIPER to prepare and conduct the Third International Reservoir Characterization Technical Conference, in Tulsa, Oklahoma, November 3-5, 1991. The First and Second conferences were held in 1985 and 1989, respectively, and were quite successful. The theme of the upcoming conference will be "Reservoir Characterization Requirements for Different States of Development," with session topics on (1) the importance of heterogeneities, (2) modeling/description of the interwell region, (3) field studies and data needs, and (4) optimization of reservoir management.

Research Support for DOE's TORIS Program

Research work in support of TORIS began in 1983 when a project was established to provide assistance in the areas of EOR project and reservoir data base management, EOR project technology and trends analysis, and evaluation of computer models and numerical simulators. During FY90, data on incentives projects for calendar years 1987 and 1988 were entered into the EOR project data bases on the PROJ computer located at the Bartlesville Project Office and the USAEOR computer maintained at the Energy Information Administration. Monthly production data were entered on 80 projects for 1987 and 65 projects for 1988. At the end of 1987, 82 projects were reported as active, while 65 were active at the end of 1988.

Trends in the application of EOR technology in the United States are analyzed annually to determine significant changes in technology. The analysis is based on current literature, trade media, and project data bases containing information on more than 1,300 projects. Changes in the frequency, EOR process type, and reservoir characteristics of project starts indicate progress of EOR applications. In 1988, 10 project starts were identified as compared to 22 for 1989. Between 1981 and 1988, the number of starts declined and this corresponded to a decline in oil prices. The figure for 1989 indicated a modest recovery in activity resulting from an increase in oil prices that began in 1987. Changes in project starts usually lag changes in oil prices. Polymer flooding projects have decreased both in actual numbers and in relation to applications of other EOR methods since 1986. Implementation of longer-term, higher cost methods such as CO_2 flooding in West Texas and steamflooding in California has continued.

Determining Three-Phase Relative Permeabilities

Over the past 6 years, NIPER has conducted research in the area of three-phase relative permeability to improve measurements used in reservoir engineering calculations which are of particular importance in the design of EOR projects where one of the flowing phases is injected to modify reservoir behavior. In multiphase fluid flow, the fluids compete for the same flow paths and cause additional resistance to flow which is described by normalizing permeabilities for each of the flowing phases at each fluid saturation condition with respect to a base permeability. This measurement and normalization process yields relative permeability data.

Current reservoir engineering practices include the use of relative permeability data in numerical simulators when predicting reservoir performance, but due to the lack of three-phase test data, correlations are usually made from available two-phase data which do not represent a true picture of multiphase flow. The objective of this research has been to improve the accuracy and reliability of laboratory measurements of two- and three-phase relative permeability considering the influence of rock and fluid properties and rock-fluid interactions. To date, the work has resulted in (1) development of an X-ray/microwave scanning instrument that effectively monitors fluid saturations, (2) design and construction of a high-pressure coreholder that is semitransparent to microwaves, and (3) development of scanning capabilities for rocks having thicknesses greater than 1 inch. During FY90, the petrophysical, capillary pressure, and relative permeability characteristics of a 700-millidarcy, fired Berea sandstone sample were investigated. Thin section analysis, computed tomography (CT) scanning, mercury injection porosimetry, centrifuge capillary pressure, and spontaneous imbibition tests were used as aids in characterizing pore and grain size distributions, capillary pressures, wettability indices, and fluid distributions. Cycle-dependent capillary pressure and relative permeability behavior for the sandstone were evaluated during the experimental program. Relative permeability experiments conducted on samples of the rock included two-phase unsteady-state oil-water tests; steady-state, oil-water and gas-water saturation tests; and three-phase, (oil-water-gas) steady-state saturation tests. Electrical resistivity characteristics were measured during the steady-state relative permeability tests.

Hysteresis was evident in the results from each multiple-cycle capillary pressure experiment. The primary effect of cycle-dependent capillary pressure changes for these samples was a reduction in the wettability index after successive drainage and imbibition cycles. Results of the research showed that hysteresis in water relative permeability values is not significant for strongly water-wet rock, while hysteresis in oil relative permeability values is not significant at high oil saturations. Predictions of secondary recovery performance for strongly water-wet rocks should not be affected by hysteresis at high oil saturations.

NIPER has gained considerable recognition for its capabilities in measuring two- and three-phase relative permeabilities at reservoirs conditions. Training has been provided to students from other countries, and several projects have been undertaken for various domestic and international oil companies through the WFO Program. These industrial projects are classified as proprietary, but the breadth of work includes an investigation of retrograde gas condensate reservoirs, determination of an optimal resin-coated gravel for gravel-packing, measurement of gas-water relative permeabilities and resistivity characteristics of reservoir rock core plugs at both ambient and reservoir temperature and pressure conditions, and measurement of crude oil-water relative permeabilities for reservoir rock core plugs at reservoir conditions.

Imaging Techniques Applied to the Study of Fluids in Porous Media

Imaging techniques developed in the Base Program are used to characterize rock heterogeneities from the pore level to core scale. Computed tomography (CT) has gained acceptance in petroleum research as a powerful tool for nondestructive measurement of variations in rock properties and fluid saturations in reservoir rock. Nuclear magnetic resonance imaging (NMRI), another imaging technology gaining favor in petroleum research, provides for nondestructive imaging of fluids in beadpacks and cores with resolution in the 25 to 1,000 micrometer range.

During FY90, the dynamics of fluid flow and trapping phenomena in porous media was investigated. Miscible and immiscible displacement experiments in heterogeneous Berea and Shannon sandstones were CT scanned to determine the effect of heterogeneities on fluid flow and trapping. Statistical analysis of pore and pore throat sizes in thin sections cut from these sandstones enabled delineation of small-scale spatial distributions of porosity and permeability. Multiphase displacement experiments were conducted using thin slabs of the two sandstones. This combination allowed for an investigation of the influence of variations in pore characteristics on fluid front advancement, fluid distributions, and fluid trapping—phenomena having a profound influence on oil production.

Although still in its early stages of development, the imaging technology is being used in support of other Base Program projects and to solve reservoir and production problems for several major oil companies and independent oil producers. Feedback from this work indicates that industry would like to see the capability developed to conduct imaging experiments at higher, more realistic reservoir pressures.

Chemical and Microbial EOR

NIPER's program in chemical and microbial EOR consists of four projects conducting research in the areas of microbial, surfactant, and alkaline flooding EOR and mobility control. The work in each project is designed to increase recovery efficiency and associated economics, to improve process predictability, and to bring promising technologies on stream as soon as possible.

Developing Improved Microbial Flooding Methods

NIPER has conducted both laboratory research and field application studies in microbial enhanced oil recovery (MEOR) for the DOE since 1983. One of the goals of this research is to establish and maintain a data base of field projects using MEOR technology. The data base provides documentation of characteristics of reservoirs used for MEOR field projects and is used to revise published screening criteria for MEOR processes. In addition to the continuing data base development, laboratory experiments were conducted during FY90 to define the key mechanisms responsible for oil mobilization. From these studies it was found (1) microbial cells are essential to the recovery mechanism with a major requirement being production of highly localized metabolites at the oil/water interface, (2) the products of microoganisms, primarily acids, alcohols, gases, and surfactants, transport ahead of the microbial cells in porous media, (3) oil recovery can be improved by injecting low concentrations of chemical additivities, and (4) oil recovery efficiency can be improved by injecting sodium bicarbonate as a preflush. From the standpoint of the reservoir rock matrix, important mechanisms are those associated with changes in the microscopic properties of interfacial tension, wettability, and adsorption. Changes in these parameters can affect fractional flow and relative permeabilities. Other recovery mechanisms traditionally associated with fluid flow changes include the production of polymeric materials and biomass.

In addition to defining the mechanisms for oil mobilization, the MEOR research team began development of simulation models capable of predicting reservoir and production behavior. Such models are essential in the design of processes that can economically recover oil from a variety of reservoir types. During FY90, a three-dimensional, three-phase, multiple-component simulator was developed. The model includes all required mechanisms and transport phenomena of microbial systems in porous media. The parameters incorporated into the model include (1) microbial growth and decay, (2) microbial deposition, (3) chemotaxis, (4) diffusion, (5) convective dispersion, (6) tumbling, and (7) nutrient consumption. Although still being tested through the acquisition of additional laboratory and field data, preliminary results indicate this simulator will be able to predict the propagation of microbes and nutrients and therefore, will be important to the design of economically acceptable MEOR injection strategies.

In 1986, knowledge gained from laboratory studies was used to design and engineer a microbial-enhanced waterflood pilot project in Delaware-Childers (OK) field. Incremental oil recovery from this pilot was 13% over that achievable by waterflood. Because of this success, an expanded field pilot was initiated in Chelsea-Alluwe (OK) field in 1990. Both field projects were jointly funded by the DOE and industrial partners under an SGP project.

Furthermore, to assure that advances in MEOR technology are made available to potential users, NIPER periodically conducts short courses emphasizing the potential of MEOR, yet stressing the need for careful engineering design which is a prerequisite to acceptable economics. These courses are of special interest to operators wishing to increase production from marginal wells in the "stripper well" category.

Development of Improved Surfactant Flooding Methods

The principal targets for surfactant flooding are directed primarily at waterflooded reservoirs containing crude oils of low to medium viscosity. Surfactant flooding, along with specific additives, provides a very flexible recovery technology that can be optimized for application over a wide range of reservoir conditions or crude oil types. However, surfactant flooding has a history of questionable economics and limited applicability in high-temperature, high-salinity reservoirs as well as those with extreme water hardness and high crude oil viscosity.

NIPER's research in surfactant flooding is focusing on criteria outlined in the AORPIP which concerns development of cost-effective surfactant formulations that meet process design requirements of low interfacial tension, low rock-adsorption properties, and tolerance to higher brine salinities and reservoir temperatures. To date, mixed surfactant systems have shown the most promise for meeting these requirements inasmuch as the concentrations of the individual components can be varied to broaden and fine-tune conditions of optimum behavior for a given reservoir.

Over the past 3 years, NIPER's research has shown that a mixed surfactant-alkaline system effectively lowers interfacial tension and reduces surfactant adsorption and precipitation by partially removing divalent ions from reservoir brine. The reduction in surfactant adsorption and precipitation improves process economics by reducing the required concentration of expensive surfactant chemicals. Other work includes development of more effective flooding systems having broader tolerance to the chemical composition of reservoirs. The work focuses on the mitigation of problems known to have adverse effects on the performance and economics of surfactant flooding processes and an improved understanding of surfactant-alkaline flooding systems that will extend current chemical flooding technology to near-term problem solving in the area of near-wellbore permeability improvement.

Project research work has provided support to industrial clients in the analyses of surfactant and surfactant-alkali mixtures proposed for field testing and the evaluation of surfactant-alcohol mixtures used for mobility control.

Development of Improved Alkaline Flooding Methods

The AORPIP calls for research to expand the application of alkaline flooding EOR to more severe reservoir environments while improving sweep and displacement efficiencies and overall process economics. Primary efforts are directed toward improvements in slug design, a better understanding of alkali/rock interactions, and the development of polymers which can operate in more difficult environments.

Over the long term, considerable research has been conducted on determining the reaction kinetics of alkaline formulations with confirmation that it is possible to prevent many of the deleterious reactions that occur between alkalis and reservoir rock. Studies on alkalis used early on by the oil industry (sodium hydroxide and sodium orthosilicate) showed them to be effective for oil displacement but unacceptably reactive with the reservoir rocks where associated dissolution of silica caused silicate scales in producing wells. This led to investigations of milder alkaline agents (sodium carbonate and sodium bicarbonate) which were less reactive with the reservoir rock matrix, but it was found that formulations using these agents were not as effective for oil displacement as those containing stronger alkalis. However, mid-term fundamental research on coalescence phenomena and dynamic interfacial tension behavior indicated that adding small quantities of surfactant to moderately alkaline formulations significantly improved recovery efficiency while minimizing deleterious alkali-mineral reactions. Recent research indicates that surfactant-alkaline formulations may be applicable to reservoirs containing low-acid crudes as well as those having high acidity. This finding significantly increases the overall target resource.

Results of this research are used to assist independent oil producers in the evaluation and use of surfactant-enhanced alkaline flooding technology.

Development of Improved Mobility-Control Methods

Dilute solutions of high-molecular-weight polyacrylamides have been used by many companies as mobility-control agents to improve the sweep efficiency of reservoir fluids. However, polyacrylamides can lose their effectiveness due to mechanical (shear) degradation and loss of injectivity. Since shear degradation is irreversible, attempts have been made to overcome the problem through the use of low-molecular-weight polymers, but this requires considerably higher polymer concentrations to achieve equivalent viscosities and can affect process economics. As a solution to both problems, research is being conducted on crosslinked low-molecular-weight polymer formulations which are not as susceptible to shear degradation and may provide good injectivity under high shear conditions.

The research has shown that crosslinked low-molecular-weight gels, suitable for mobility control, can be formulated using Cr(III), pH 4.8, and Cr(VI), pH 6.8 crosslinkers. Neutral pH can be attained with aluminum citrate crosslinker. Experiments indicate that crosslinking bonds can be broken under a high shear condition and will reheal (reform) under a subsequent low shear condition. This permits the healed gelled polymer to regain viscosity and reduce water mobility as it flows through the reservoir. Thus, crosslinked low-molecular-weight gels not only overcome the shear degradation problem but also improve injectivity over that of conventional high-molecular-weight polyacrylamides. Simulation runs indicate polymer gel treatment should begin close to the time of water breakthrough and that the depth of gel penetration is dependent on slug size.

Thermal and Gas EOR

Base Program research is being conducted on two projects in the area of gas flooding: one designed to advance the state of the art in miscible gas flooding processes and the other targeted on improved mobility control in gas flooding. Additionally, two Base Program thermal recovery projects are underway with goals of determining the utility of steamflooding for light oil recovery and improving mobility control and sweep efficiency of injectants used in heavy oil recovery.

Gas Miscible Displacement

The injection of miscible and immiscible gas into oil reservoirs accounts for about 29% of the commercial EOR production in the United States. In West Texas carbonate reservoirs, CO_2 flooding has been sufficiently successful to justify building CO_2 supply pipelines several hundred miles long. However, it is generally known, and substantiated in the AORPIP, that recovery can be increased by improving sweep efficiency of the gas and reducing viscous fingering and channeling which result from formation heterogeneities. Another problem results from deposition of wax and asphaltene materials in the near-wellbore region of producing wells, causing lower oil production and increased costs for workovers. Nitrogen gas (N_2) is also used for enhanced recovery in areas where economic supplies of CO_2 are unavailable.

Early studies under this project were concerned with improved recovery using N_2 since it is more economical and more plentiful than CO_2, or light hydrocarbon gases, and is often used as a chaser gas following slug injections of other recovery gases. Because of its high minimum miscibility pressure (MMP), the injection of N_2 for EOR has been effective in deep light-oil, high-pressure reservoirs. The research has shown that the composition of reservoir hydrocarbons, especially the quantity of light hydrocarbons from methane through pentane, is an important consideration for reducing MMP. The mid- to near-term research effort has focused on problems associated with CO_2 oil displacement. To date, project researchers have developed an accurate property prediction package for CO_2 density, viscosity, and physical property correlations for CO2 heavy oil mixtures, and results from this work have been transferred to industry for use in a gas-EOR process design. Recent work has focused on studies of transport and adsorption phenomena of surfactants and commercial foaming agents used in generating foam for improved sweep efficiency. Mathematical models have been developed describing the transport and adsorption phenomena of surfactants in porous media. The models take into account the convection, dispersion, capacitance, and adsorption effects of surfactant foaming agents.

Additional models are under development for predicting wax and asphaltene deposition. A simplified asphaltene solubility model has been developed and tested. It employs a polymer solution theory for the asphaltene-oil solution and treats the asphaltene as a polydispersed mixture. The developed model combines regular solution theory with the Flory-Huggins polymer solutions theory to predict maximum volume fractions of asphaltene dissolved in oil. The model requires evaluation of vapor-liquid equilibria, first using an equation of state and then calculations of asphaltene solubility in the liquid phase. A state-of-the-art technique for C_7+ fraction characterization was used in developing this model. For wax material, a model based on the solid-liquid solution theory is under development. Preliminary results indicate it is more accurate than those found in the literature and can predict wax appearance, temperature, and composition with reasonable accuracy.

Improved Mobility Control and Sweep Efficiency in Gas Flooding

The successful application of gas flooding processes for oil recovery depends upon the ability of the injected gas to contact the oil. Although CO_2 flooding processes potentially have high displacement efficiencies, oil recovery can be substantially reduced by poor sweep efficiency and unfavorable gas mobility. Under normal reservoir conditions the injected CO_2 is considerably less viscous, with a lower density than the target oil being displaced, and has a tendency to bypass the oil and lead to early gas breakthrough. To mitigate problems of poor sweep efficiency and inadequate mobility control, recent research has focused on two processes which have shown considerable promise for improving sweep efficiency and mobility control: the use of surfactant systems to generate foams in situ and the use of cosolvents or entrainers (supercritical fluid additives) to enhance the phase behavior and solvent properties of injectant and reservoir fluids.

Interest in the use of foams has resulted from their potential application as mobility-control agents, and the increase in their use is acknowledged in the AORPIP. Although successfully tested in laboratory coreflood experiments, the transfer of foam technology to the field has not advanced sufficiently because of the lack of adequate models or scaling rules to describe its behavior. To overcome the many complexities associated with the use of foams, an approach is being taken that combines both laboratory data and modeling for the development of screening and predictive methods which can optimize gas-foam flooding applications. Early laboratory studies were designed to observe and quantify the behavior of foam including the effects of foam quality, shear rate, surfactant concentration, foam texture, temperature, etc.

At the 1990 SPE/DOE Symposium on Enhanced Oil Recovery, IITRI/NIPER staff presented a paper on foam research. From this study, in which a radial flow model was used, it was found that surfactant concentration tends to drop sharply near an injection wellbore. This finding raised several important questions: Can results from slim tube experiments and linear corefloods be extrapolated geometrically to radial conditions found at the wellbore? Can foams be successfully generated and propagated by adjusting critical surfactant solution volumes, concentrations, and injection sequences for idealized radial flow, or must these parameters be further adjusted to account for discontinuous or heterogeneous fluid flow patterns? These questions must be answered before gas-foam injection can reach its maximum potential.

Entrainers, in addition to enhancing the phase behavior and/or solvent properties of fluids, are able to increase selectivity in supercritical extraction processes. For gas miscible flooding, these materials have the potential to improve displacement efficiency by increasing the solubility of marginally soluble components in crude oils and to improve mobility control from the viscosity contributions of both the entrainer and solubilized components. Studies with entrainers confirm that certain materials can enhance mobility control and improve the economics of recovery.

Developing Thermal Processes for Light Oil Recovery

Although steamflooding is generally associated with the recovery of heavy oil resources, studies are being conducted for the DOE on the potential application of steamflooding to enhance oil recovery from light oil reservoirs (>20° API gravity). Studies to date have shown that steam distillation is the primary mechanism in improving oil recovery from light oil reservoirs, whereas viscosity reduction by steam is the principal mechanism in heavy oil recovery. It has also been determined that reservoir wettability plays an important role, with the research indicating that oil-wet reservoirs can be prime candidates for light oil steamflooding. Furthermore, laboratory research has been accelerated through development of a numerical, thermal simulator for enhancing the design and analysis of laboratory steamfloods and steamfloods in which diverters are used to force steam into previously unswept zones.

One of the tasks under this project is to provide support to DOE's cooperative agreement with the Venezuelan Ministry of Energy and Mines through biennial meetings of Annex IV. At the most recent meeting, IITRI/NIPER staff discussed research defining the role of wettability alteration for improved oil recovery in light oil reservoirs. In contrast to reservoirs in which the oil-containing surface is water-wet, oil-wet reservoirs are not conductive to waterflood because of high water requirements, early water breakthrough, and water disposal problems. However, results of two-dimensional coreflood experiments showed that steamflooding changes the wettability to a more water-wet condition and thus can be a viable EOR process for oil-wet, light-oil reservoirs. Other laboratories participating in Annex IV include INTEVEP, Stanford University, and Lawrence Livermore Laboratories. This cooperative effort has proved to be very beneficial to all participants as it provides for the rapid dissemination of research results, minimizes duplication of effort, promotes interaction among various researchers, and provides direction for future research.

Developing Thermal Processes for Heavy Oil Recovery

Steamflooding of heavy oil reservoirs (<20° API gravity) is a mature technology and currently contributes 7% of total U. S. daily oil production. The majority of the Nation's steam injection projects are concentrated in the State of California where most of the oil is produced by major oil companies. Through DOE funding, NIPER is attempting to bring the technology to independent operators who may have a limited background in thermal EOR. To assist the independents, an operator's guide on thermal EOR, based on an assessment conducted during FY90 on California's ongoing thermal operations, is being developed. This undertaking is similar to assistance provided to independents during the 1950s on the advantages of waterflooding which was provided by one of NIPER's predecessor organizations, the U. S. Bureau of Mines Bartlesville Petroleum Experiment Station.

Although thermal recovery technology has been improved, sweep efficiency is still a major problem. Research in this area has concentrated on the implementation of cost-effective surfactants for the generation of foams for improved steam diversion and overcoming problems of gravity override. Early work focused on design and construction of a two-dimensional (2-D) experimental model for laboratory-scale determinations of the effectiveness of foaming surfactants for profile modification improvement. From the 2-D experiments, along with recent experiments with 1-D quartz sandpacks, it has been found that high-temperature, foam-forming surfactants control the gravity override of steam in oil reservoirs by diverting the steam to deeper regions, and that the degree to which this can be accomplished depends on oil composition, surfactant type, surfactant concentration, and other operating variables. These results confirm that process parameters required in minimizing steam override are reservoir specific and must be tailored accordingly.

In FY89, project researchers began development of a numerical steamflood simulator for use in history matching data from laboratory experiments and parameter sensitivity studies. In FY90, the parameters sensitive to a typical laboratory steamflood process were identified and included: steam quality, steam injection rate, initial oil saturation, oil viscosity, oil volatility, and rock porosity and permeability. However, additional development will be required as a result of time-step sensitivity tests which showed that the model was highly time-step sensitive. Large time steps tend to destabilize the model leading to convergence difficulties.

FUELS RESEARCH

The Fuels Research (FR) Department continues its multiphase program in developing methods for the separation and identification of individual compounds and classes of compounds in petroleum and alternative feedstocks, in the measurement of thermodynamic properties of organic materials, and in determining the performance and emissions of fuels burned in engines.

The research work supports DOE's Fossil Energy AEPT Subprogram which has responsibility for the cross-cutting fundamental and exploratory research related to the evaluation, extraction, processing, and upgrading of oil, gas, oil shale, tar sands, and underground coal gasification resources. The FR Program encompasses the entire realm of liquid and gaseous fuels—from the time they are extracted, through the processing sequence, to commercial utilization.

In FY90, the total effort consisted of two Base Program projects, 18 projects under the Supplemental Government Program (SGP), and 41 projects in the Work for Others (WFO) Program. The two Base Program projects provided stability to a continuing effort in processing and thermodynamics and fuel chemistry that have been underway at the Bartlesville Center for more than 70 years. Clients in the SGP and WFO Programs depend on the developed expertise to help solve problems associated with fuels processing and emissions. Research and/or consulting services are provided to the U. S. Navy, Strategic Petroleum Reserve, American Petroleum Institute, Defense Fuel Supply Center, Environmental Protection Agency, Design Institute for Physical Properties Research, and Consumer Product Safety Commission. Titles of nonproprietary projects are listed in appendix B and portray the types of problem-solving research being performed outside the Base Program.

Processing and Thermodynamics

Information available for the processing of light petroleum crudes has become a part of the "permanent" literature following years of study by this and other research laboratories, academia, and the oil industry. The precision and accuracy of component determination and thermodynamic property measurements of these crudes have permitted the design of processes to produce desired products with high efficiency. However, alternative feedstocks contain considerable quantities of hetero- and diheteroatomic compounds, polynuclear aromatics, and organometallic compounds—some of which produce reactive components during processing. The production of fuels containing even small quantities of reactive components can cause fuel utilization problems of instability, incompatibility, and gum formation.

The data generated for the light crudes are generally not transferrable to heavy oil refining processes, but the use of such data is an approach still pursued in spite of considerable literature defining the differences in processing requirements. This inverted approach to crude processing results in a loss of industrial competitiveness due to the tendency to overdesign process equipment, with performance far below optimum conditions. An alternate approach is to define optimum conditions via thermodynamics and then search for catalysts that will meet the appropriate design requirements. As an example, results of FR's thermodynamic equilibria studies of aromatic nitrogen compounds provide convincing evidence that, with an appropriate catalyst, nitrogen can be removed more efficiently from polycyclic aromatic compounds at temperatures below 650° F, rather than the 650° to 750° F currently used in refinery processes.

Thermochemical and Thermophysical Properties of Organic Nitrogen- and Diheteroatom-Containing Compounds

Determining the relationship between molecular structure and the chemical and physical properties of organic nitrogen- and diheteroatom-containing compounds and polycyclic aromatics is the major goal of this project. The research effort is based on an assessment of thermodynamic needs developed in FY86. Briefly, this assessment was to determine the thermodynamic properties of priority compound types, i.e., organic nitrogen compounds, diheteroatomic compounds, organic oxygen compounds, and organometallic compounds. To date, thermodynamic properties have been determined for 22 nitrogen-, 4 diheteroatom-, 18 oxygen-, 2 sulfur-containing compounds, and 17 polycyclic aromatic hydrocarbons. The research approach is to build correlations for a given class of compounds which are based on the extrapolation of data from a selected group of highly purified compounds within that class. This concept, denoted as "group additivity," speeds data acquisition and provides for near-term problem solving. Applications of these data to acceptable processing include: determination of optimum reaction sequences; optimum reaction compositions, temperatures, and pressures for desired conversions; cooling/heating requirements for reaction vessels; capacity of heat exchangers; and size, strength, and complexity of separation vessels. The nitrogen work is scheduled for completion in FY91 and the diheteroatom work in FY94.

Related thermodynamic research on heteroatom compounds in coal is funded by FE's Advanced Research Coal Liquefaction Program and on shale oil and tar sand oil by FE's Office of Energy Research. The work has increasing importance because fuels made from unconventional (heavier) feedstocks are being used to compensate for the shortfall now being experienced in the United States as a result of the rapid decline in production (and reserves) of light petroleum crudes. With oil imports now approaching the 50% level, alternative feeds are expected to be a substantial part of future refinery inputs. The research efforts in each area are complementary to the Base Program work.

Proprietary research is performed on specialized client projects. The data and correlations provided allow these clients to optimize processes. One such client tripled the desired product yield by changing temperature and pressure conditions within existing reactors to those more favorable to the reaction equilibria being sought. Literature citations of NIPER's work indicate the data and correlations are widely used throughout the private sector.

Fuel Chemistry

The Bartlesville Center has many years of experience in the analysis of compounds found in petroleum distillates. Work between 1948 and 1972 resulted in the development of analytical procedures for the identification of more than 200 sulfur compounds in petroleum. During this period, it was found that separating the distillates into acid, base, and neutral fractions greatly reduced the complexity of the characterization procedure. This separation scheme was then extended to the characterization of compound types in heavy ends of light petroleum and today, with modifications and improvements, is used for the separation and identification of problematic components in heavy crude distillates and resids.

The expertise developed during the Base Program research has been extended to assist others through the SGP and WFO Programs. One major SGP project provides support to the Strategic Petroleum Reserve where recent work has shown that sludge formation in the oil caverns is not a matter of concern. Other SGP projects have employed techniques developed under this project to investigate the thermal and storage stability of fuels. A study on the stability of light cycle oils has led to a proposed mechanism for sediment formation in diesel fuels. The majority of work for WFO projects has been in the resolution of problems associated with refining and product quality.

Development of Analytical Methods for the Analysis of Heavy Crudes

Initial project work focused on a long-term study to develop analytical methods for the identification of compound types present in Cerro Negro (Venezuelan) heavy crude, a crude known to be one of the most difficult to characterize. The Cerro Negro research work resulted in the publication of seven major technical papers on the development of procedures for the separation and identification of constituents in this crude. First, a paper on the procedures for the routine determination of the chemical and physical properties was prepared. This was followed by five papers on the detailed separation and analysis schemes for the characterization of (1) acid, base, and neutral fractions; (2) acidic compounds; (3) basic compounds; (4) aromatic hydrocarbons: and (5) sulfur compounds. The final report summarizing the methods development and characterization procedures was published in January 1990.

Following completion of the Cerro Negro work, the direction of research shifted toward developing an understanding of the behavior of compound classes during resid upgrading. Coking or carbon deposition is a common occurrence in many refining processes, particularly those employed for upgrading distillation residues. Carbon deposits also typically contain portions of sulfur, nitrogen, and metals which are particularly harmful in reducing the activity of processing catalysts. Catalyst regeneration processes are ineffective in removal of metals codeposited with carbon; sulfur and nitrogen oxides present in regeneration gases require removal for environmental reasons.

During FY90, the relative tendencies of compound classes to form coke and to codeposit heteroatoms were determined. More specifically, compound class fractions from five resids (>1000° F) were prepared using liquid chromatographic (LC) techniques developed in earlier work. Carbon residue yields and heteroatom distributions of carbon residues versus volatiles were determined for each LC fraction. The carbon residue yield and distributions of sulfur, nitrogen, nickel, vanadium, and iron varied appreciably for the various compound classes in a given resid. This type of information is useful in optimizing refining processes so that the amount and impact of coke formation can be reduced. A similar investigation of coking behavior of various compound classes in the presence of catalytic cracking catalysts is proposed as future work.

II. INTRODUCTION

Fiscal year 1990 completes the seventh year of research under the cooperative agreement established in 1983 between the Department of Energy (DOE) and IIT Research Institute (IITRI) for operation of the National Institute for Petroleum and Energy Research (NIPER). Under this agreement, NIPER's mission has three major thrusts: the first and primary is to perform work for DOE's Office of Fossil Energy (FE) through an approved Base Research Program; second, to conduct research work through a Supplemental Government Program (SGP) for non-DOE government agencies and any additional work for DOE not included in the Base Program; third, to help industrial clients solve their technical problems through a Work for Others (WFO) Program. The Bartlesville Project Office (BPO), which is collocated with NIPER, serves as the DOE administrator of the cooperative agreement.

During the latter part of FY90, events occurring in the Middle East quickly underscored the importance of the Nation's petroleum reserves and the need to continue development of technologies capable of recovering as much of our remaining resource as possible. Even before these events, there was growing concern over the need to import over 45% of the Nation's oil supply and the difficulty of reversing this trend due to the lack of predictable, cost-effective technologies to stem the tide of domestic well abandonments once conventional primary and secondary recovery methods reach their economic limits. Because of this situation, and the fact that conventional methods recover only about one-third of the original oil in place, the DOE refocused its research goals to help ensure that reservoir access is maintained on substantial portions of the estimated 343 billion barrels of oil and 132 to 386 TCF of gas remaining in domestic reservoirs. To attain these goals, the DOE issued its National Energy Strategy–Advanced Oil Recovery Program (NES-AORP) in April 1990. The Advanced Oil Recovery Program Implementation Plan (AORPIP) outlines an integrated, highly targeted research, development, and demonstration program focusing on near-, mid-, and long-term objectives that will bring new EOR and advanced drilling technologies to the field within the earliest possible timeframe.

The goal of the new strategy is to maximize the economic producibility of the domestic oil and gas resource. The near-term objective (fully effective within 5 years) is to preserve economic access to productive portions of the remaining oil resource by instituting a well-designed technology transfer program—involving the Federal government, the states, service companies, and various research organizations—that will help ensure that currently proven technologies are made available to oil and gas producers who might benefit from their use. The AORPIP details a reservoir classification system that has identified reservoir classes having the greatest recovery potential and are in the most danger of early abandonment. The DOE estimates that meeting the near-term objective could result in production of an additional 17 billion barrels of oil that might otherwise be lost.

If technology transfer is successful in the near term, DOE projects an additional 61 billion barrels of oil may become recoverable in the mid term (fully effective within 10 years) by implementing currently identified, but yet-to-be-proven technologies. Here, the DOE takes a problem-solving approach that will maximize specific reservoir producibility by describing reservoir heterogeneities, architecture and flow paths; reservoir simulation and process design; and testing and evaluation of production technologies.

The long-term effort, expected to reap benefits the first part of the 21st century, is to develop sufficient fundamental understanding of the geoscience and reservoir fluid flow patterns so that additional oil can be recovered from the 265 billion barrels that remain after near- and mid-term objectives are met.

To help accomplish the stated objectives, the AORPIP authorizes continued research in five principal categories: (1) reservoir description methods, tools, instrumentation, and modeling; (2) extraction techniques to include drilling, secondary, and tertiary recovery; (3) environmental technology covering air, water, solid waste, and wetlands management; (4) petroleum chemistry/processing covering constraints on production and refining problems; and (5) technology transfer.

Within the Base Program, this Center provides supporting research in nearly all of the above categories, and the work is performed and managed under the organizational structure shown in figure 1.[1] The Energy Production Research (EPR) Department is responsible for a total of 12 projects in the areas of Geotechnology, Chemical and Microbial EOR, and Thermal and Gas EOR. These projects address categories 1 and 2 of the supporting research outlined above. The Fuels Research (FR) Department is responsible for two Base Program projects in category 4. Presently, the only environmental work (category 3) being performed is under the SGP and WFO Programs, but much of the present work is the result of expertise gained under former Base Program projects. Environmental considerations are paramount in all new technical innovations. Category 5, technology transfer, is NIPER's principal product and will be emphasized throughout this report since it is plays a crucial part in the successful implementation of the AORPIP.

As shown in table 1, 11 of the EPR projects are funded under FE's EOR Light and Heavy Oil Programs. The remaining project (BE12), and the two projects in Fuels Research are funded under FE's Advanced Exploration and Process Technology (AEPT) Program.[2] The AEPT Program provides for advanced instrumentation and fundamental and exploratory research on the cross-cutting issues associated with the processing, upgrading, and utilization of heavy petroleum feedstocks and alternative feeds from oil shale and tar sands. The DOE programs are managed by the BPO which has been delegated the lead assignment for implementing FE's EOR and AEPT Programs through a number of projects executed by (1) NIPER, which utilizes the Federal equipment and facilities at Bartlesville; (2) industrial and university research organizations; and (3) National Laboratories.

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[1]NIPER is not performing fuels/engines research for DOE under the Base Program although such a category is shown in figure 1 for the Fuels Research Department. The fuels/engines work is, however, important to NIPER's total program as it provides information on the changes and overall acceptability of today's transportation fuels.

[2]Individual research projects are numbered in a simple code: A letter "B" representing the Base Program; a letter "E" or "FR" representing the EPR and FR Departments, respectively; and a project number. Thus, BE1 indicates Base Program project No. 1 of Energy Production Research.

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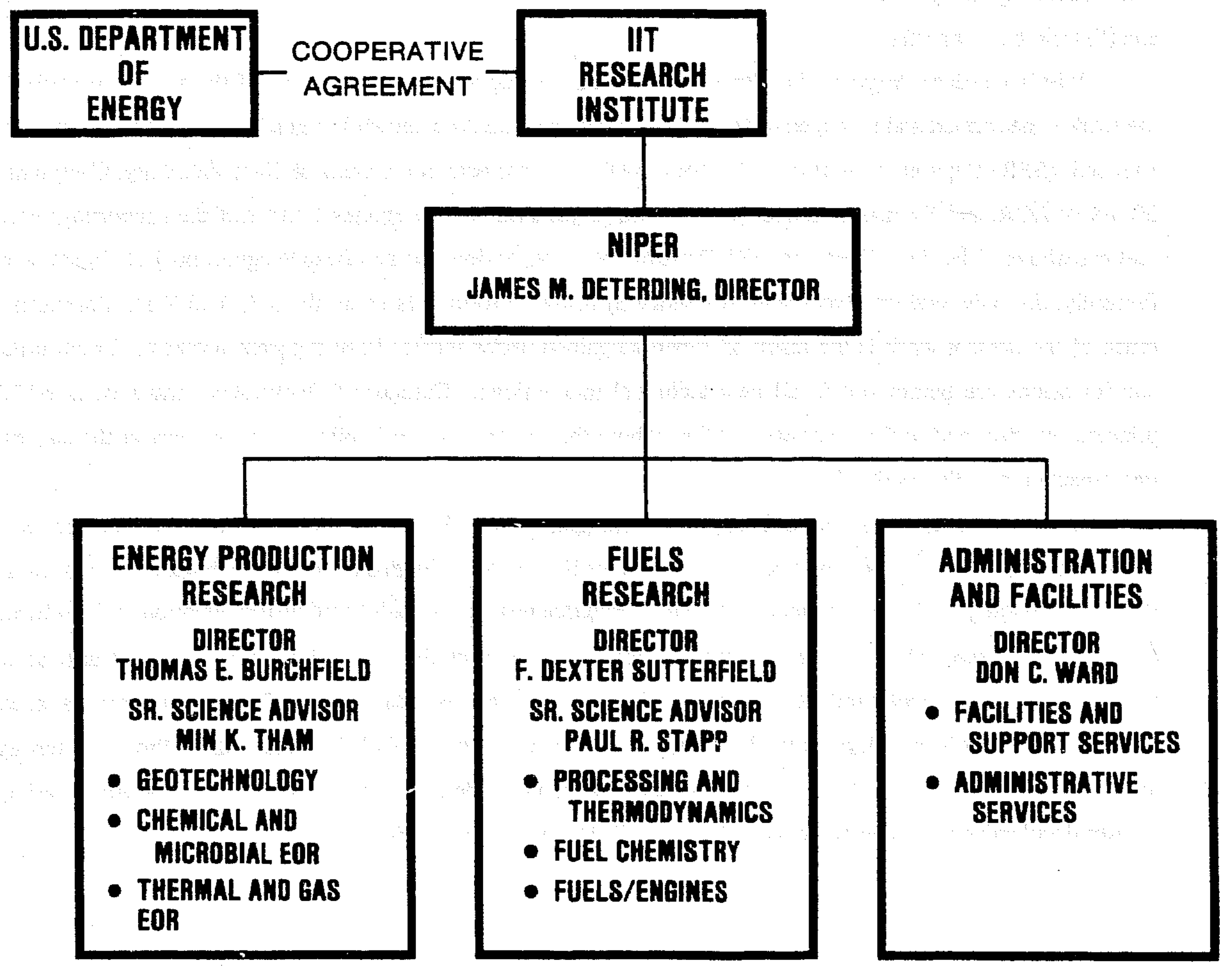


FIGURE 1. - NIPER Organization.

TABLE 1. - NIPER FY90 Base Research Program

Project		DOE FE Program[1]	Funding, $K
ENERGY PRODUCTION RESEARCH			
Geotechnology			
BE1	Reservoir Assessment and Characterization	EOR-LO	797
BE2	TORIS Research Support	EOR-LO EOR-HO	140 59
BE9	Three-Phase Relative Permeability	EOR-LO	301
BE12	Imaging Techniques Applied to the Study of Fluids in Porous Media	AEPT	391
Chemical and Microbial EOR			
BE3	Development of Improved Microbial Flooding Methods	EOR-LO	297
BE4A	Development of Improved Surfactant Flooding Systems	EOR-LO	600
BE4B	Development of Improved Alkaline Flooding Methods	EOR-HO	138
BE4C	Development of Improved Mobility-Control Methods	EOR-LO	196
Thermal and Gas EOR			
BE5A	Gas Miscible Displacement	EOR-LO	376
BE5B	Development of Methods To Improve Mobility Control and Sweep Efficiency in Gas Flooding	EOR-LO	256
BE11A	Thermal Processes for Light Oil Recovery	EOR-LO	295
BE11B	Thermal Processes for Heavy Oil Recovery	EOR-HO	199
	Total EPR Base Projects		4,045
FUELS RESEARCH			
Processing and Thermodynamics			
BFR3	Thermochemistry and Thermophysical Properties of Organic Nitrogen- and Diheteroatom-Containing Compounds	AEPT	350
Fuel Chemistry			
BFR2	Development of Analytical Methodology for Analysis of Heavy Crudes	AEPT	295
	Total FR Base Projects		645
	TOTAL BASE PROJECTS		4,690

[1]Abbreviations: EOR = Enhanced Oil Recovery; LO = Light Oil; HO = Heavy Oil; AEPT = Advanced Extraction and Process Technology

Discussions affecting NIPER's research and administrative activities, planning, occupational safety and health, and quality assurance are held on a weekly basis by the management staff.

Under an Approved Annual Research Plan, NIPER's FY90 EOR program was based on earlier DOE guidance with specific goals: (1) to foster geoscience research—with special emphasis on reservoir characterization—to provide for more efficient extraction of mobile and immobile oil and (2) to develop environmentally and economically acceptable advanced thermal, chemical, gas, and novel EOR processes based on the fundamental aspects of oil recovery. Thus, the majority of work focused on improved recovery processes for wide application and, although generic in nature, improved the basic understanding of recovery processes which was a primary goal of the long-term program established in 1983. The new plan builds upon this understanding but directs future research to specific target reservoirs and recovery processes.

The FR Department is addressing yet another issue that results from depletion of the Nation's light oil resource: the need to become more reliant on heavy petroleum and alternative hydrocarbon feedstocks (shale oil, tar sand oil, etc.). Today, many refineries are increasing product yields by blending small quantities of heavier crudes with conventional feedstocks, but the addition of too much or the wrong type of heavy crude can cause refining difficulties and result in end-products that may be unstable when stored or incompatible when blended or burned as fuel. NIPER's approach to solving these problems is to study the complex chemistry involved in processing satisfactory fuels through characterization studies. Once characterized, the thermodynamic properties of the problematic components are determined in order that they can be economically removed from process steams or converted to nonreactive species during the refining process.

The Base Program research effort continues to provide continuity and stability to the oil, gas, and fuels research program which began at the Bartlesville Center over 70 years ago. Although some projects continue long-term investigations of difficult and complex problems, others have advanced markedly and are now fully capable of helping DOE establish near-term objectives of the AORPIP and provide problem-solving research to clients in the SGP and WFO Programs. In FY90, 35 SGP projects and 71 WFO projects were active with total funding of over 6 million dollars. The SGP Program has shown an increase in research volume of 21% annually since its inception in 1988. Research volume for the WFO Program has grown at a phenomenal average annual rate of over 95% since its beginning in the latter part of 1983. This ability to interact with other government agencies and industry not only assures technology transfer but provides a feedback medium for the identification and prioritization of areas needing additional research.

The new AORPIP elaborates on the importance of technology transfer between research organizations, industry, and the states. NIPER is fully aware of this need and makes contributions of technical information by way of the client programs; through technical publications and presentations; sponsoring and cosponsoring symposia, meetings, and conferences; supplying data base support and development to both DOE and industry; redesigning and improving reservoir simulators; participating in related professional society and association activities; cooperating with other oil-producing countries through DOE-sponsored programs; and working closely with independent oil producers.

In FY90, the research program accounted for more than 56 publications by NIPER authors, of which 37 were submitted to DOE as program deliverables. The remaining 19 reports were published either in technical journals or symposia proceedings and resulted from information and data acquired from a combination of Base, SGP, and WFO research efforts. Seven of these reports were published in the proceedings of the Seventh SPE/DOE symposium on EOR and represented 5% of the total number of papers presented. On a quarterly basis, newly developed data generated through the Base Program are provided to the DOE for inclusion in its publication, *"Quarterly Progress Review of Research on Enhanced Oil Recovery."* This report is disseminated by the DOE to more that 2,400 recipients, including major oil companies, independent operators, service companies, consultants, and universities. Approximately 250 copies of the report are distributed internationally.

In addition to the publications, staff scientists and engineers presented 24 technical papers at national and international symposia. Participation in such meetings is an essential part of continued progress in developing state-of-the-art technologies and promotes technology transfer. On an international scale, NIPER's research is supporting DOE's cooperative research agreement with the Venezuelan Ministry of Energy and Mines through biennial meetings of Annex IV participants. Presentations at these meetings are carefully evaluated as to content and are used to provide direction for future research in light- and heavy-oil steamflooding. Other laboratories participating in Annex IV include INTEVEP, Stanford University, and Lawrence Livermore Laboratories.

Data base analytical support is being provided to the DOE Program Manager responsible for the Tertiary Oil Recovery Information System (TORIS). TORIS contains field test information resulting from DOE cost-shared and tertiary incentive projects (TIP), predictive models and reservoir/geological engineering data on domestic oil fields, a historical EOR project data base, and a comprehensive data base of crude oil properties. This data base system was used extensively in classifying reservoirs for study in the AORPIP and will be used to coordinate future research efforts based on new information to be provided by laboratory and field studies.

NIPER's Petroleum Product Surveys provide fuel property values that are significant both in the manufacture of fuels and in the design of nearly all types of end-use equipment, from small heaters and boilers to jet engines. Biennial reports on motor gasolines (winter and summer) and annual reports on aviation turbine fuels, heating oil, and diesel fuel oils are distributed to some 700 clients which include fuel manufacturers, fuel marketers, designers of heating systems, the military, and consultants. This statistical information is useful in forecasting fuel quality, compiling local and national averages of fuel properties, and supplying the data base needs of various regulatory agencies. These surveys have been conducted at the Bartlesville Center since 1918 and were funded by the DOE and its predecessors for several years; however, the data base is now self-sustaining through a multiclient program established in 1986. The American Petroleum Institute has contributed to this program through the years and continues to provide program guidance.

Considerable time and effort have been devoted to the development of improved reservoir simulators. The BOAST black oil simulator, available in the public domain, has been modified extensively. Several major oil companies are now utilizing NIPER's BEST simulator (computerized version of BOAST) and BEST VHS (vertical/horizontal/slanted well) simulator. Other simulators are currently under development for the DOE.

Incoming technical information is maintained by the Center's library. The facility is open to the public and routinely provides services to the research and administrative staffs of both NIPER and BPO. In addition to the store of knowledge available in some 20,000 books and 250 current technical journals, information is accessible though several on-line data bases and through the national OCLC interlibrary loan network. On-line data bases include Dialog, Orbit, STN, Chemical Abstracts, and ITIS/DOE Energy.

The following pages of this report contain information on the research performed on 14 Base Program projects by the Energy Production and Fuels Research Departments; and, because of its importance to the new AORPIP, how the research results are being transferred to others through various media and SGP and WFO Programs.

III. ENERGY PRODUCTION RESEARCH

In FY90, the Energy Production Research (EPR) Department was responsible for 12 Base Program projects, 17 SGP projects, and 30 projects for clients in the WFO program. The Base Program projects continued to provide the results of research commissioned under DOE's former Enhanced Oil Recovery Program Plan and FY90 Advanced Extraction and Process Technology Subprogram. Late in the fiscal year, the DOE authorized several new SGP projects and requested a change in direction of some Base Program projects to provide immediate analytical support and research targeted toward the new Advanced Oil Recovery Program.

This report presents a summary of research work performed on the 12 Base Program projects during FY90 and briefly describes progress made since initiation of the long-term, high-risk research effort in the latter part of 1983. Some projects continue to seek solutions to very difficult and complex problems, while others have advanced to the application stage and are now providing new or improved technologies to NIPER's governmental and industrial clients.

Under DOE's multiyear sponsorship of geotechnology research, the Center's researchers have developed the knowledge and equipment necessary for characterizing oil reservoirs, determining rock-fluid interactions, and establishing fluid flow properties of injectants used for secondary and tertiary oil recovery. During FY90, a unique automated X-ray/microwave instrument was developed for use in Base Program projects to measure two- and three-phase relative permeabilities under both steady- and unsteady-state reservoir conditions. A patent application has been filed for this novel apparatus, and an equipment manufacturer is currently marketing an instrument based on the design and computer software in this patent. Training is provided to staff members of other companies that have acquired the commercial instrument. Through the WFO Program, this equipment has been successful in determining the effects of waterflooding on formation damage for a reservoir in South America and used to design production strategies for a major gas condensate reservoir by determining the critical condensate saturation and relative permeability at reservoir conditions.

During FY89, computed tomography (CT) instrumentation was acquired for use in conjunction with an existing nuclear magnetic resonance imaging (NMRI) capability. Development of this equipment has been rapid. By the end of FY90, it was being used for accurate measurements of reservoir rock properties and to describe, systematically, variations in rock pore structures. The specialized imaging facility supports all EPR projects dealing with reservoir characterization and fluid flow properties and is used to assist industrial clients through the WFO Program.

FY85 and 86 Base Program studies on determination of reservoir descriptions, sampling, and measurement of outcrop samples from the Shannon formation in Naval Petroleum Reserve No. 3, Teapot Dome (WY) field have led to a multiclient project studying quantified spatial variations of reservoir parameters. Two years of research have been successfully completed on this project, and a third is being planned. Clients in the project include two domestic oil companies and Agip Spa of Milano, Italy and RIPED of Beijing, China.

NIPER scientists have been actively involved in the modification and development of several reservoir simulators and have gained considerable experience in the process. The BOAST black oil simulator, available in the public domain, has been modified extensively making it more user friendly and versatile. As a result, three new process-specific simulators have been designed and are being used to enhance the research work in several Base and SGP projects and have been made available to industry. One simulator, designated as BEST, has proved its utility for Base Program research in calculating relative permeabilities for coreflood experiments, effects of shale laminations on waterflood recovery, and effects of faulting during line drive waterflooding. The BEST simulator has been modified for personal computers (PC-BEST) and is now being used by ten major and independent oil producers. The BEST-VHS simulator is a versatile vertical/horizontal/slanted well simulator which is assisting independent oil producers contemplating the drilling of horizontal wells. This simulator is to be modified for personal computer use in FY91 under an SGP project. The BEST-GEL simulator has been developed for predicting performance of polymer flooding and to define improvements in this type of flooding when specially designed polymer gels are applied. It has been used to assist independent operators seeking information on profile modification.

As a result of Base Program research in microbial enhanced oil recovery (MEOR), an applications process has been patented. NIPER has worked with both the DOE and independent producers, through cost-shared field demonstrations, on two microbial-enhanced waterflooding projects. One project was successfully completed in Nowata County, Oklahoma, and an expanded project is currently in progress in Rogers County, Oklahoma. Because of the interest in MEOR, several short courses have been conducted on the economic viability of microbial processes for improved oil recovery. These courses have been of interest to major oil company representatives, independent oil producers, and participants from other countries.

Developments from past research in surfactant-enhanced alkaline flooding technology have resulted in a NIPER patent. A cost-shared field project to demonstrate the technical and economic feasibility of this technology is scheduled for FY91 under an SGP project. In addition, a surfactant-enhanced alkaline flooding system has been designed for application in a large carbonate reservoir in Texas where a pilot project is being planned. NIPER has also received a patent for an improved steamflooding process and is assisting one of the world's largest chemical companies in developing a novel mobility control process for commercial application. Work with another major oil company has resulted in the development of a powdered biopolymer product. This product has been tested in a field trail where it worked successfully for water shut-off.

Prior to 1988, two Base Program projects identifying environmental concerns associated with petroleum technologies were completed and the results reported in the public domain. As a result of this work, additional expertise was developed which today allows NIPER to perform environmental research under the SGP Program. Assistance is provided to the DOE by evaluating new regulations that could impact the oil industry. Information for the 1990 edition of the U. S. Army Corps of Engineers Toxic and Hazardous Materials Agency's publication "Installation Restoration and Hazardous Waste Control Technologies" was prepared by NIPER. A new environmental study for FY91 is concerned with development of an underground implant for the detection of soil gas.

Based on previous work for DOE's Tight Gas Sands project, expertise developed in hydraulic fracturing and stimulation resulted in a major WFO investigation of a tight gas reservoir in China. For this project, highly specialized laboratory tests were conducted to aid in the design of well stimulation techniques such as hydraulic fracturing and acidizing. These processes were successfully implemented in the field.

Geotechnology

DOE's AORPIP calls for an interdisciplinary, problem-solving approach to maximize the producibility of selected reservoir classes to include advanced description of reservoir heterogeneities, architecture and flow paths; reservoir simulation and process design; and testing and evaluation of advanced production technologies. EPR's Geotechnology Section provides support in all of these areas based on past DOE-funded research in reservoir assessment and characterization, three-phase relative permeability measurements, and development of advanced instrumentation to aid in the determination of reservoir descriptions and rock-fluid interactions at micro- and macroscopic scales. Also, several advanced mathematical simulators have been developed and made available to industry to help solve reservoir engineering problems. Geotechnology also provides data base support to the DOE Program Manager responsible for the Tertiary Oil Recovery Information System (TORIS).

It is well recognized that the single most important technical constraint to successful recovery of residual oil is the lack of understanding of reservoir architecture and how inherent heterogeneities in the rock matrix affect fluid flow. Thus, a need exists for better understanding of the effects of rock properties, rock-fluid interactions, and natural and artificial fracturing on process performance. To accommodate this need, IITRI/NIPER and DOE have cosponsored two international conferences on reservoir characterization, the first in 1985 and the second in 1989. Because of the ever increasing interest in achieving a better understanding of reservoir architecture, a third jointly-sponsored reservoir characterization conference has been scheduled for November 3-5, 1991, in Tulsa, Oklahoma.

NIPER's studies in reservoir characterization are conducted under Base Program project BE1. The purpose is to obtain a better understanding of the anatomy of a reservoir thereby optimizing reservoir management strategies. A methodology (fig. 2) has been developed over the past 4 years which consists of the application of various tools to subsurface reservoirs and using modern analogs for construction of an integrated geological/engineering model. For the geological model, core-calibrated downhole logs provide information on sedimentology, stratigraphy, structure, and geochemical components. Single and interwell, pressure-transient well tests; tracer tests; production/injection/pressure monitoring; wireline logs; and laboratory rock/fluid analyses provide data for the engineering model which, in turn, provides information on horizontal and vertical sweep efficiencies, displacement efficiency, formation damage, and effectiveness of remedial actions. This combined geological/engineering approach has been tailored to the effective characterization of barrier island reservoirs for predicting residual oil saturation and flow patterns of injected and produced fluids through computer simulation.

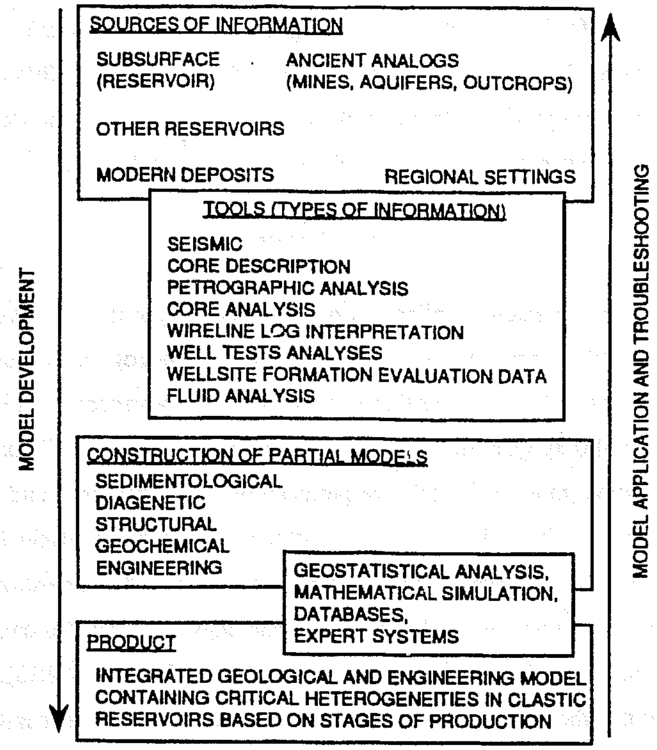


FIGURE 2. - Reservoir Characterization Methodology.

The simulation model was developed from data collected from Bell Creek (MT) field shoreline barrier formations. Later, geological data from a tertiary incentive project (TIP) and the surrounding area of Unit 'A' in Bell Creek field were used to refine the model and evaluate, quantitatively, the influence of critical heterogeneities in the TIP area. The analysis determined that under a favorable mobility ratio the role of depositional heterogeneities was extremely important in terms of production and injection performance. Additionally, diagenetic effects were found to moderately or, in some cases, significantly deteriorate reservoir properties and drastically influence production performance. The geologic structure of the reservoir also played an important role. Faulting disrupted the continuity of flow units and adversely affected fluid movement (sweep and displacement efficiencies). Structural dip of the reservoir was important for improving production performance in areas where the oil bank moved, by line drive flooding, up dip against a stratigraphic pinchout of the barrier sandstone. The performance of chemical flooding was influenced significantly by the presence of anisotropy and especially by variations in the amount of clay distribution in the area.

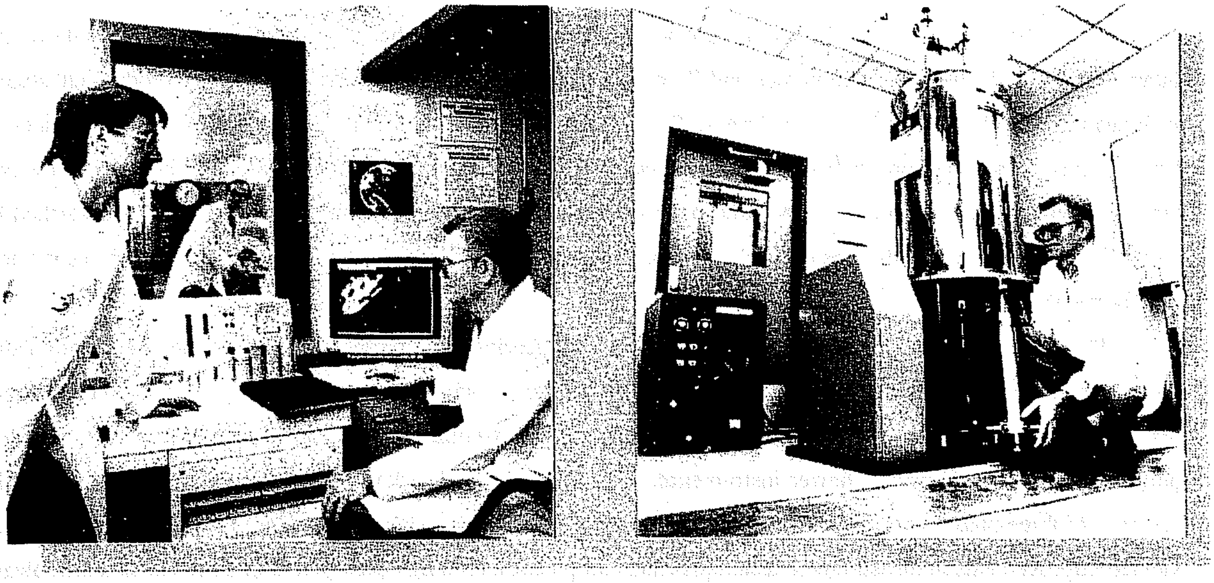
Although development of the current geological/engineering model was based on shoreline barrier systems, the methodology should be applicable to the fluvial-dominated deltaic reservoirs chosen as Class 1 under the AORPIP. However, until the research requirements for deltaic reservoirs are fully defined, NIPER is proposing the study of a second barrier system in Patrick Draw (WY) field for FY91. The study is designed to test the methodology and refine shoreline barrier reservoir descriptions. Shoreline barriers are ranked in the top 10 of priority classes outlined in the DOE plan.

Once the general condition of a reservoir is known, it then becomes necessary to understand the interrelationships between formation rock and fluid flow characteristics of the reservoir. Primary production usually includes moving phases of oil, gas, and brines. Two-phase flow occurs in secondary recovery when a fluid such as brine is injected to boost production, and multiphase flow occurs when chemicals or gases are injected to recover tertiary oil using EOR techniques. The additional resistance to flow from injecting these materials is described by normalizing relative permeabilities for each of the flowing phases at each fluid saturation condition with respect to a base permeability.

Through years of research, major oil company laboratories and commercial laboratories have found that measuring three-phase relative permeabilities at equilibrium or steady-state conditions provides the most reliable results, but few correlations have been developed for use in simulators that can accurately predict reservoir performance. Now, however, newer instrumental techniques are under development which greatly enhance the accuracy of three-phase, steady-state flow measurements. Toward this end, research in Base Program project BE9 has yielded improvements in measurement techniques and equipment including development of an X-ray and microwave scanning instrument for monitoring fluid saturations in rocks having thicknesses greater than 1 inch. In addition, a high-pressure core holder was designed and constructured which is semitransparent to microwaves. Previous three-phase experiments were conducted with rocks ranging in permeability from 600 to 2,000 millidarcies. The work proposed for FY91 is to continue the studies with homogeneous sandstones having absolute permeabilities in the 150 to 400 millidarcy range. The results will be compared with earlier data to build a foundation that will ultimately lead to the development of correlations for the type of simulators required in accurately predicting reservoir performance.

Instrumental techniques being developed in Base Program project BE12 were used in FY90 to characterize rock samples from the pore level to core-scale for projects BE1 and BE9. Computed tomography (CT) is a powerful tool for nondestructive measurement of variations in rock properties and fluid saturations in reservoir rock. Development of nuclear magnetic resonance imaging (NMRI) is another nondestructive imaging technology and is used to image fluids within cores. The Center's NMRI capability presently allows imaging of fluids in beadpacks and cores with resolutions as low as 25 and 120 microns, respectively. The CT instrument is capable of imaging fluid distributions for both miscible and immiscible floods in heterogeneous cores approaching 2 inches in thickness.

Research work in developing the capabilities of CT and NMRI began in FY89. Since that time, the technology has advanced rapidly and is now being used for rock-fluid characterizations in several Base Program projects and to solve formation and production problems in oil and gas reservoirs for industrial clients. At present, studies of flow processes are performed at ambient conditions, but clients are interested in imaging recovery processes at more realistic reservoir pressures, and work is proposed for FY91 to conduct experiments at higher pressures.



Capabilities in computed tomography (CT) and nuclear magnetic resonance imaging (NMRI) provide for core-scale measurements of rock heterogeneities and fluid saturation distributions ranging from 25 to 1,000 micrometers. Shown at the left is the control room of the CT laboratory with the scanner room in the background. In the photo at the right, a sample is being introduced into the superconducting magnet of the NMR spectrometer where it will undergo imaging analysis.

Base Program project BE2 is also managed under Geotechnology. This project provides research support to DOE's Tertiary Oil Recovery Information System (TORIS) in the areas of EOR project and reservoir data base management, EOR project technology and trends analysis, and evaluation of computer models and numerical simulators. The TORIS data bases contain field information, predictive models, and reservoir/geological/engineering information on hundreds of domestic oil fields. Originally a three-state classification system, TORIS is being expanded to include most of the known oil resources in major producing states and presently includes geological and engineering information on 3,700 reservoirs representing 72% of total U. S. oil-in-place. It has been instrumental in planning the reservoir classification system outlined in the AORPIP and will be used to monitor all new information resulting from future research.

Project BE2 provides an annual report on trends associated with the application of EOR technology in the United States. The analysis is based on current literature, trade media, and project data bases containing information on more than 1,300 projects. Changes in the frequency, EOR process type, and reservoir characteristics of project starts show how the application of EOR is progressing. The research proposed for FY91 includes but is not limited to (1) maintenance of specific TORIS data bases assuring consistency of data entry and computerized routines, (2) transfer of 1989 production data for EOR cost-shared and incentive projects into the EOR project data base, (3) evaluation of simulators and computer models required for the TORIS Program, and (4) assistance to the Bartlesville Project Office in answering inquiries concerning publicly available simulators.

Considerable portions of the described Base Program research efforts have been transferred to other government agencies and industry and will be discussed in the FY90 project summaries for Base Program projects BE1, BE2, BE9, and BE12 which follow.

RESERVOIR ASSESSMENT AND CHARACTERIZATION

Principal Investigator:	Matt M. Honarpour[3]
BPO Project Manager:	Edith C. Allison
Contract No.:	DE-FC22-83FE60149, Project BE1
Funding for FY90:	$797,000 (EOR-Light Oil)
Period of Performance:	October 1, 1989 – September 30, 1990

Objective

The broad goal of the Department of Energy for geoscience research is to develop methods for determining both mobile and immobile oil saturation distribution in reservoirs and evaluating suitable methods to recover that oil. This project addresses that goal by developing a better understanding and quantification of heterogeneity factors that influence the movement and trapping of fluids in reservoirs. The continuing objective of this project is to develop an improved methodology for effective characterization of barrier island reservoirs for predicting the residual oil saturation (ROS) at interwell scales in reservoirs and the flow patterns of injected and produced fluids. Specific objectives for FY90 were: (1) to select a second shoreline barrier system for testing the integrated reservoir characterization methodology developed earlier, (2) to apply the detailed results of systematic reservoir characterization to production prediction in a barrier island system, and (3) to develop and improve reservoir description techniques to provide reliable input data for performing reservoir simulation.

Research Summary

This project is unique in systematically addressing the integration of geological and engineering information for major genetic variations in a deposition system. Shoreline barriers, see (fig. 3), have been chosen to develop and demonstrate this integrated approach to reservoir characterization because these systems contain a substantial amount of petroleum resource in the United States that can be a target for recovery by infill drilling or enhanced oil recovery (EOR). In the near term, this reservoir characterization methodology will assist producers in implementing more effective reservoir management strategies such as placing infill wells or planning fluid diversion.

In previous years, project researchers investigated a microtidal, wave-dominated, progradational shoreline barrier system that has been a prolific producer – the Bell Creek field in Montana. The first task during FY90 was to select another shoreline barrier system to validate the methodology developed earlier. The Almond formation of Patrick Draw (WY) field was selected from 18 candidate reservoirs. The Almond formation is a mesotidal system in which tidal inlet, tidal delta, and tidal channel facies are more dominant than in a microtidal system like the Muddy formation at Bell Creek. Advantages of Patrick Draw field over other shoreline barrier fields are: the field is located within the Rocky Mountain region, geographically similar to Bell Creek field; the Almond formation has extensive outcrops within 10 miles of subsurface production; cores and logs are available from the U.S. Geological Survey and

[3] *Currently with Mobil Oil Company. For information about this project, contact Michael P. Madden of NIPER.*

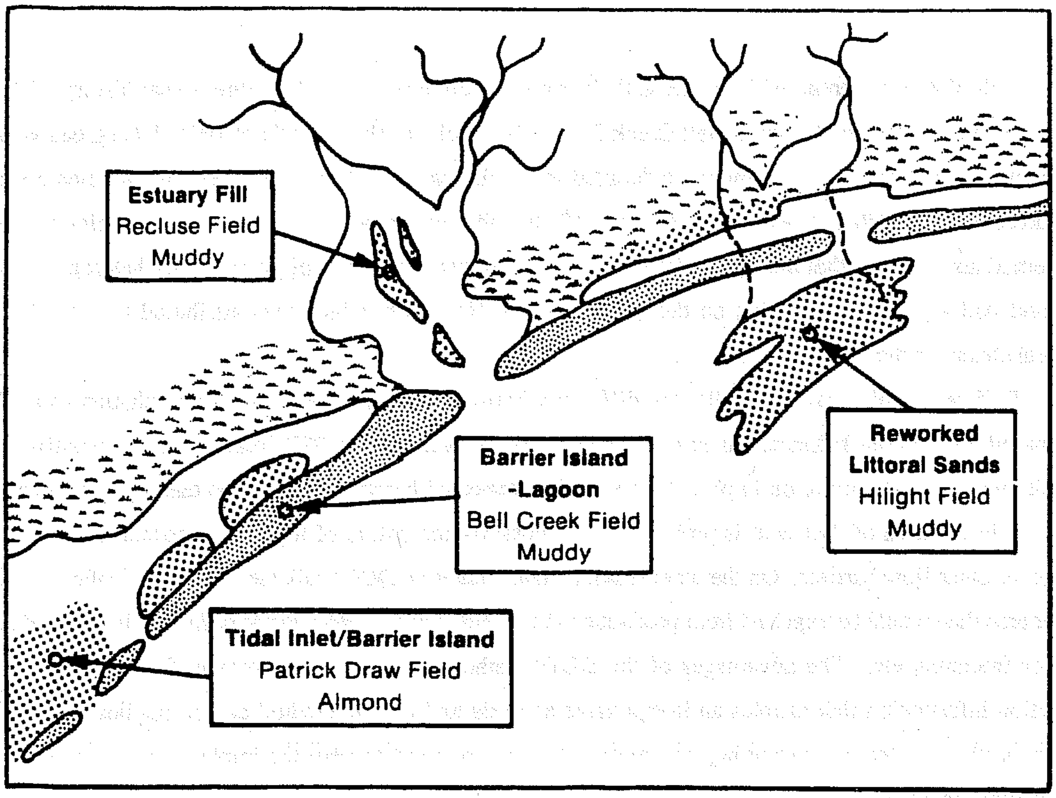


FIGURE 3. - Diagrammatic map showing relative locations of ancient oil productive shoreline barrier sandstones in Wyoming and Montana. (Modified from R. R. Berg, Reservoir Sandstones, Prentice-Hall, Inc., Inglewood Cliffs, NJ, 1986, p. 284.)

oil companies; and the Almond formation represents a different "end member" of barrier deposition as compared to the Muddy formation of Bell Creek. Similarities and differences between the Almond and Muddy formations will indicate the extent to which the behavior of shoreline barriers can be generalized meaningfully.

Only a preliminary geological analysis of the Almond formation was completed during FY90; the analysis, involving more engineering aspects, will continue through FY91. The abundance of detrital feldspar, 8% by weight or 4 times that in the Muddy formation at Patrick Draw, is related to the origin of common secondary intraparticle porosity within the producing Almond formation sandstones. The average permeability is two orders of magnitude less than that for the Muddy formation. The small size of pore throats indicates that the formation is susceptible to damage from mobile fines.

Improvements were made in reservoir characterization methodology through a continued investigation of information from Bell Creek field. Readily available information was analyzed using methods such as Hall plot analysis, comparison of material balance and volumetric methods of calculating oil in place, and correlations of log and core data. A new approach to reservoir characterization using fractal analysis was investigated to analyze log signatures in order to quantify the distribution of heterogeneities within a reservoir.

Hall plots were prepared for water and chemical injection wells for the entire 6-year history of the Tertiary Incentive Project (TIP) conducted in Bell Creek field. The results of the analysis of Hall plots agreed well with the identification of heterogeneities using more detailed reservoir characterizations: the Hall plot method gives a strong indication of the variability in permeabilities, skin effects, and drainage areas for improved reservoir characterization. The method also showed that micellar-polymer injection reduced the effects of permeability heterogeneity and fluid flow, and had a pronounced effect on the appearance of Hall plots which was attributed to local variations in structural characteristics.

Differential oil in place (DOIP), the difference between the oil in place based on volumetrics and the oil in place based on material balance, has been calculated for 54 wells in the TIP area. A highly positive DOIP at a particular well indicates more oil in place than would be expected based on production data and, therefore, drainage efficiency in the area of that well is probably low—possibly indicative of high clay content, sealing faults, well damage, or other flow barriers. On the other hand, a highly negative DOIP indicates that a particular well is draining a larger area than would be expected from production data—indicative of clean sands or favorably oriented conducting faults or fractures, etc. The advantages of the DOIP method are (1) the requirement for only readily available production information that enables an inexpensive analysis and (2) the method can be applied before the end of primary production thereby providing information that can be used to plan the implementation of waterflooding, infill drilling, or EOR.

Log data represent the cumulative response of 2 to 3 feet of rock, whereas core data represent the characteristics of rock at a point. The results of the correlation of log and core data from Bell Creek field indicated that (1) the texture of the rock, characterized by properties such as grain size distribution and sorting, affected oil saturation distribution; (2) the initial oil saturation in clean sands was uniformly high; (3) the effects of texture and clay content were more pronounced after primary and secondary production due to non-uniform sweep—particularly in areas of high clay content; and (4) the best petrophysical properties were observed in massive sandstones having large grain sizes and low-angle dipping laminae with good vertical permeability, whereas the poorest properties were in clay-rich, bioturbated, or highly burrowed sandstones.

A computer program to process many types of data using fractal analysis has been developed. Only preliminary results have been obtained, and the work is to continue into FY91. This method will be applied to the problem of recognition, quantification, and characterization of log signatures.

Process Utilization and Technology Transfer

Project BE1 is designed to develop reservoir characterization methodology that can be applied in similar reservoirs. Although the systems used to develop and validate the methodology are related to shoreline barriers, the general methodology is applicable to other depositional systems. Other projects conducted during the year relied and built upon the knowledge gained in this project as described below.

The reservoir characterization team examines log data with well locations in Patrick Draw (WY) field. This field is under study to determine the extent to which the architecture and production behavior of shoreline barrier deposystems can be generalized. Shoreline barriers are in the top 10 priority class of reservoirs outlined in DOE's Oil Research Program Implementation Plan.

The second year of a multi-client project to quantify spatial variations of reservoir parameters in shelf ridge deposits was concluded. This project was sponsored by three international oil companies. The first year, a quantitative geologic model was developed for the Shannon formation based on field descriptions and measurements of outcrops and cores, sedimentology, and permeability and porosity distributions from more than 1,200 core plugs obtained from the formation outcrops. The outcrop-based model was compared with the subsurface productive zone in both shallow and relatively deep reservoirs to determine the degree of similarity between the outcrop and the reservoirs. For the second year the purpose of the project was to determine the effect of the spatial arrangement and density of core-plug scale permeability data in deriving grid-block scale values for numerical simulation. The results indicate that greater detail in simulator input is required when the reservoir is heterogeneous and the viscosity ratio between injected and formation fluids is adverse. Failure to account for the distribution of discontinuous, high-permeability sand layers will result in an overly optimistic prediction of waterflood production. The presence of small-scale heterogeneities will increase dispersivity of a water front, decrease the effective permeability, reduce fingering; and, thereby, improve sweep efficiency and increase oil recovery.

NIPER also began participating in research with the DOE, under an SGP project, to help implement the AORPIP. This plan, which focuses on deltaic reservoirs containing the majority of domestic oil reserves, is designed to determine the general characteristics of those reservoirs; identify the types of drilling, completion, and production technologies that would be most effective for those reservoirs; and direct research, development, and demonstration projects to exploit those reservoirs in the most effective manner. NIPER's participation in the program, particularly an analysis of the characteristics of fluvial-dominated deltaic reservoirs selected as Class 1 by DOE, will continue into FY91.

An SGP project to develop methods for mapping the distribution of clays in petroleum reservoirs was begun. Clays in reservoir rocks can be a serious impediment to effective exploitation of hydrocarbon resources and can complicate the determination of hydrocarbons in place using wireline logs. This project was undertaken (1) to develop techniques for mapping the types and volumes of clays and cation exchange capacity in clastic reservoirs from signature analysis of log responses, (2) to determine the limitations of existing wireline logs in mapping clay distributions in reservoir rocks in older fields, and (3) to identify data needed in supplementing log data for a more rigorous interpretation of clayey formations. This project began late in FY90 and will continue through FY91 and into FY92.

An SGP project has been established to substantiate fluid migration patterns into, within, and out of a reservoir by adapting natural isotopic geochemical techniques to the requirements of quantitative hydrodynamic reservoir modeling The first phase of the project, funded into FY91, will analyze the feasibility of using isotopic methods for the identification of crossflow based on the results of similar or distinctive isotopic compositions reported from individual producing intervals in multireservoir systems; select a candidate hydrocarbon reservoir where an indication of dynamic conditions exists and isotopic techniques could be applied successfully to validate hydrodynamic models; determine the best diagnostic spectrum of stable and radioactive isotopes for effective detection of crossflow in the selected hydrocarbon reservoir; and provide recommendations for a sampling program. If the first phase is successful, a second phase will be proposed to apply the methods recommended in phase 1.

Finally, members of the team involved in the development of reservoir characterization methodologies are working with other NIPER research teams involved in a wide variety of energy production research topics such as the assessment of heavy oil resources in the United States, an analysis of trends in the application of EOR processes, numerical simulation, and environmental protection.

Publications[4]

Selection and Initial Characterization of a Second Barrier Island Reservoir System and Refining of Methodology for Characterization of Shoreline Barrier Systems, by M. Szpakiewicz, R. Schatzinger, S. Jackson, B. Sharma, A. Cheng, and M. Honarpour. Dept. of Energy Report No. NIPER-484, 1990. NTIS Order No. DE91002216.

Quantified Spatial Variations of Reservoir Parameters in Shelf Sandstone Ridge Deposits, by M. Chang, L. Tomutsa, and S. Jackson. Client Report No. NIPER-B08677-2, April 1990.

[4] *Appendix C provides ordering information for DOE reports prepared by NIPER.*

Selection of a Second Barrier Island Reservoir System for Expanding the Shoreline Barrier Reservoir Model and Refining NIPER Reservoir Characterization Methodology, by M. Szpakiewicz, R. Schatzinger, S. Jackson, B. Sharma, A. Cheng, and M. Honarpour. Dept. of Energy Report No NIPER-472, 1990. Available from DOE Bartlesville Project Office, Bartlesville, OK.

Application of Natural Isotopes in Groundwater for Solving Environmental Problems—Final Report, by Michael Szpakiewicz. Dept. of Energy Report No. NIPER-450, 1990. NTIS Order No. DE90000223.

Critical Heterogeneities in a Barrier Island Deposit and Their Influence on Primary, Waterflood and Chemical EOR Operations, by B. Sharma, M. Honarpour, M. Szpakiewicz, and R. Schatzinger. *SPE Formation Evaluation*, v. 5, No. 1 , March 1990, pp. 103-112.

Petroleum Reservoir Analysis, by L. Koederitz, A. Harvey, and M. Honarpour. *Introduction to Petroleum Reservoir Analysis*, Gulf Pub. Co., 1989.

Determining the Productivity of a Barrier Island Sandstone Deposit from Integrated Facies Analysis, by B. Sharma, M. Honarpour, S. Jackson, R. Schatzinger, and L. Tomutsa. *SPE Formation Evaluation*, v. 5, No. 4, December 1990, pp. 413-420.

Presentations

Determining the Productivity of a Barrier Island Sandstone Deposit from Integrated Facies Analysis Based on Log and Core Data and Fluid Production, by B. Sharma, M. Honarpour, S. Jackson, R. Schatzinger, and L. Tomutsa. Pres. at the Soc. Pet. Eng. Ann. Tech. Conf. and Exhib., San Antonio, TX, October 8-11, 1989. SPE paper 19584.

Injection-Production Monitoring — An Effective Method for Reservoir Characterization, by M. Honarpour and L. Tomutsa. Pres. at the Seventh SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, April 22-25, 1990. SPE/DOE paper 20262.

Effects of Reservoir Heterogeneities on Production Performance in Bell Creek (MT) Field, a Barrier Island Reservoir, by M. M. Honarpour. Pres. at the SPE Forum, Denver, CO, July 1990.

TORIS RESEARCH SUPPORT

Principal Investigator:	James F. Pautz
BPO Project Manager:	Chandra M. Nautiyal
Contract No:	DE-FC22-83FE60149, Project BE2
Funding for FY90:	$140,000 (EOR-Light Oil)
	$ 59,000 (EOR-Heavy Oil)
Period of Performance:	October 1, 1989 – September 30, 1990

Objective

The purpose of this ongoing project is to provide research support to the DOE's Tertiary Oil Recovery Information System (TORIS) in the areas of EOR project and reservoir data base management, EOR project technology trends analysis, and computer simulation.

Research Summary

Information acquired in this project concerning ongoing EOR projects and EOR technology trends is used to continually update the TORIS-EOR data bases.

Since 1982, the DOE has collected data from operators participating in the DOE Tertiary Enhanced Oil Recovery Incentives Program. Data on these incentive projects for calendar years 1987 and 1988 were entered into the EOR project data bases on the computer located at the Bartlesville Project Office (PROJ) and the computer of the Energy Information Administration. Monthly production data were entered on 80 projects for 1987 and 65 projects for 1988. At the end of 1987, 82 projects were reported as active, and 65 were reported active at the end of 1988. These data undergo several phases of verification before being entered into the data bases: visual checking of the accuracy of data entry, comparison of several data fields of new data with data already in the data bases, checking of numeric and character format, and verification of annual production figures.

Trends in the application of EOR technology in the United States are analyzed annually to determine significant technology changes. This analysis is based on current literature, trade media, and project data bases containing information on more than 1,300 projects. Changes in the frequency, EOR process type, and reservoir characteristics of project starts show how the application of EOR is progressing. Ten EOR project starts were identified for 1988 and 22, for 1989. Between 1981 and 1988, the number of project starts declined corresponding to a decline in oil prices. The figure for 1989 indicated a modest recovery in EOR activity as a result of increased oil prices since 1987. Changes in project starts usually lag changes in oil prices. Since 1986, polymer flooding projects decreased both in actual numbers and in relation to other EOR methods. Longer-term, higher-cost methods, such as CO_2 flooding in West Texas and steamflooding in California continue to be implemented. The correlation of project starts with oil price is shown in figure 4.

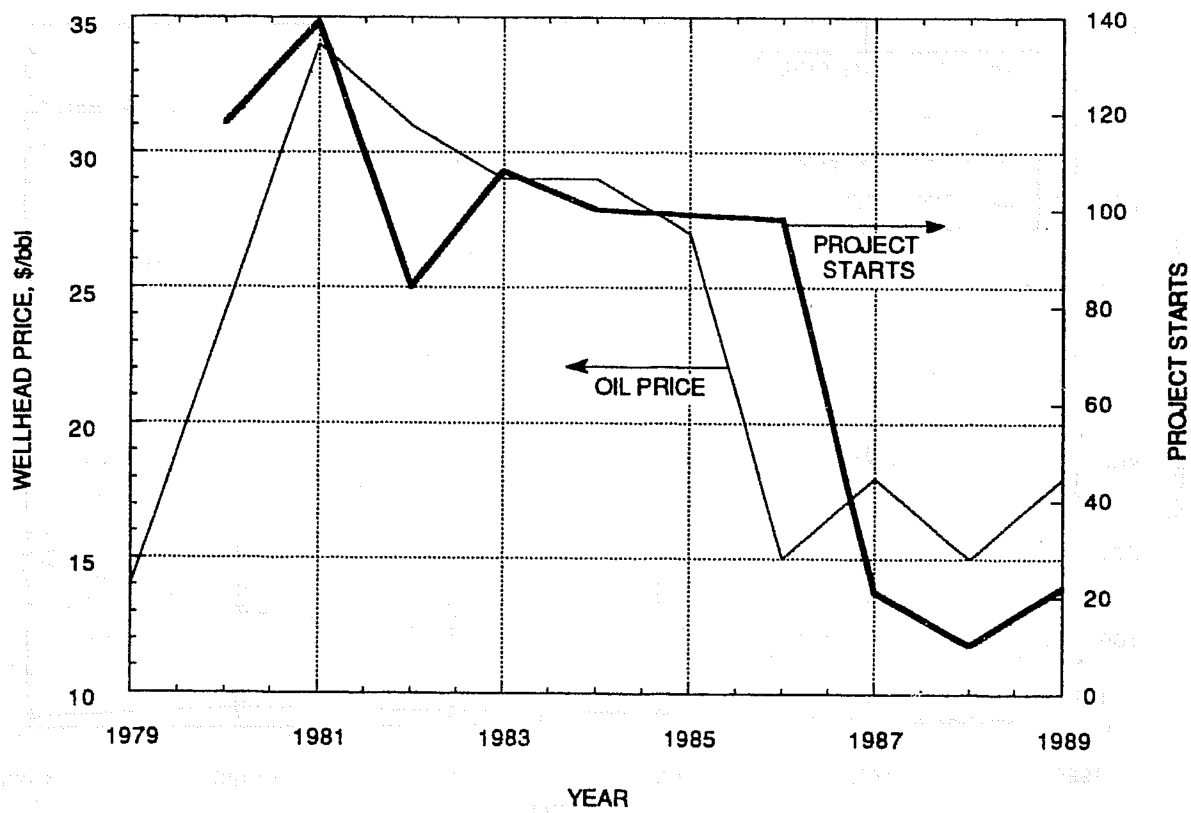


FIGURE 4. - EOR project starts compared to oil price (Refiner's cost).

Although the number of EOR project starts has declined drastically since 1986, production due to EOR has not declined correspondingly. In fact, production at the end of 1989 was 18% higher than that in 1986 when oil prices dropped by 50%. Production from both chemical and thermal methods has decreased, whereas production from gas projects has increased. EOR is being implemented selectively when it fits in with existing long-term plans and where the necessary extensive infrastructure exists. The trends indicate continued application of selected EOR processes in spite of price decreases. A comparison of the production from various EOR methods is presented in figure 5.

The interest in novel EOR technologies (microbial EOR, mine-assisted EOR, radio frequency oil production, alkaline/surfactant/polymer processes, etc.) is continuing at a low, but increasing level. Plans for microbial EOR projects continue, and applications of horizontal drilling are being considered. Field applications of these novel methods are cautious and on a small scale.

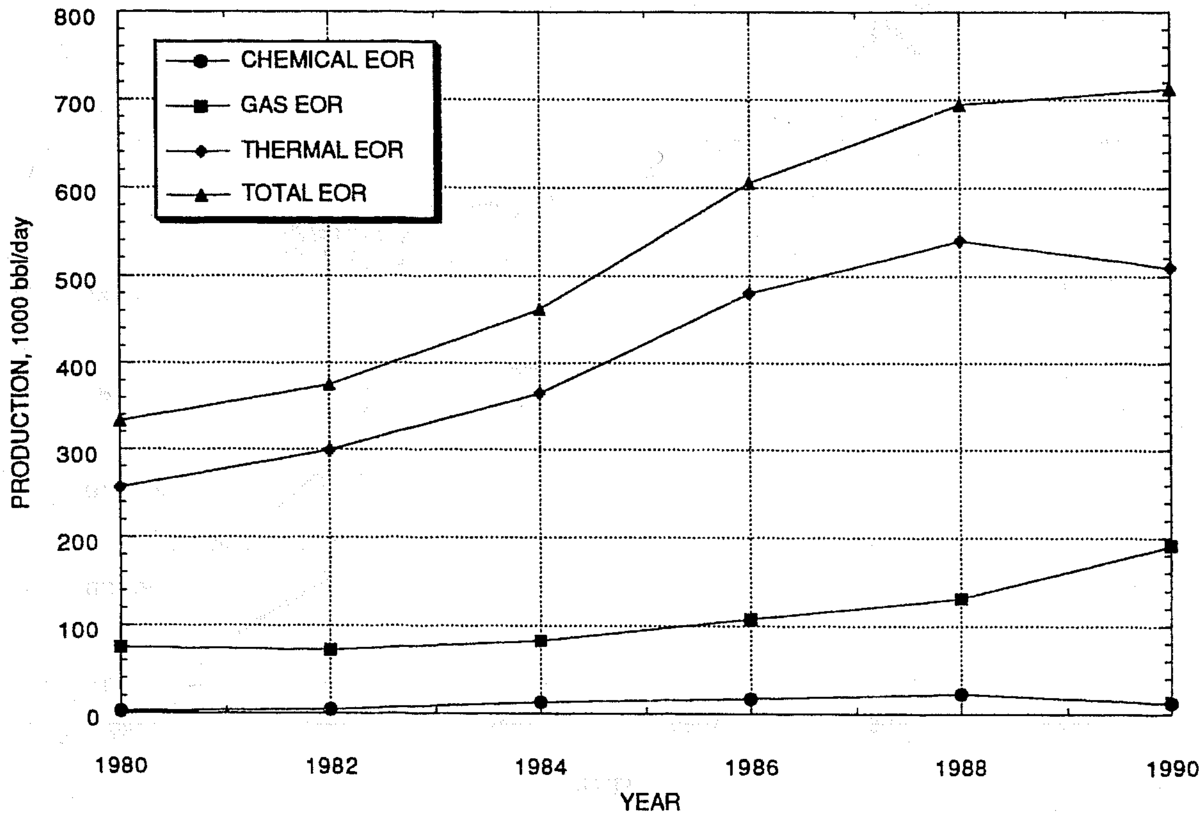


FIGURE 5. - EOR production in the United States, including Alaska.

Process Utilization and Technology Transfer

Knowledge gained in project BE2 is being used to assist the DOE in the immediate implementation of the DOE AORPIP, which relies heavily on information contained in the TORIS data base system. Most of the new work is being performed under the SGP Program and reflects the urgent need to be able to determine the applicability and success of EOR in a particular class of reservoirs which, in turn, determines the course of future EOR research. The first phase of an effort to develop a relational reservoir data base on the BPO computer is being undertaken in an SGP project. This should expand the availability of the reservoir information collected by the TORIS program during the past 9 years. Production data of projects from the DOE 1978 tertiary incentive program are being collected in another SGP project. These data are added to the EOR project data bases to give complete histories of a wide spectrum of EOR projects—both successful and unsuccessful. Information is frequently requested from this data base by DOE, industry, and NIPER personnel.

Publications

Review of EOR Project Trends and Thermal EOR Technology, by J. Pautz, P. Sarathi, and R. Thomas. Dept. of Energy Report No. NIPER-461, 1990. NTIS Order No. DE90000225.

Incentive Project Data Additions to Project Data Bases 1987 and 1988 by C. Sellers. Dept. of Energy Report No. NIPER-494, 1990. Available from DOE Bartlesville Project Office, Bartlesville, OK.

Survey of DOE Incentive Program Projects for Calendar Years 1987 and 1988, by J. Pautz and C. Sellers. Dept. of Energy Report No. NIPER-486, 1990. Available from DOE Bartlesville Project Office, Bartlesville, OK.

Applications of EOR Technology in Field Projects – 1990 Update, by J. Pautz and R. Thomas. Dept. of Energy Report No. NIPER-513, 1990. NTIS Order No. DE91002219.

THREE-PHASE RELATIVE PERMEABILITY

Principal Investigator:	Daniel R. Maloney
BPO Project Manager:	Edith C. Allison
Contract No:	DE-FC22-83FE60149, Project BE9
Funding for FY90:	$301,000 (EOR-Light Oil)
Period of Performance:	October 1, 1989 – September 30, 1990

Objective

The objectives of this project in FY90 were to improve the reliability of laboratory measurements of three-phase relative permeability for steady- and unsteady-state conditions in core samples and to investigate the influence of rock, fluid, and rock-fluid properties on two- and three-phase relative permeabilities. Relative permeability data accurately depicting multiphase flow effects are frequently required for reservoir engineering calculations. Considerations often include the displacement of oil by simultaneous gas and water flow and an estimation of the volume of oil recovered as well as that left in place after primary and secondary production. Enhanced recovery processes also involve three-phase flow in which one of the flowing phases is injected to modify reservoir behavior or to improve petroleum production.

Research Summary

During FY90, the petrophysical, capillary pressure, and relative permeability characteristics of a 700-md, fired Berea sandstone were investigated. Thin section analysis, computed tomography (CT) scanning, mercury injection porosimetry, centrifuge capillary pressure, and spontaneous imbibition tests were used as aids in characterizing pore and grain size distributions, capillary pressures, wettability indices, and fluid distributions. Cycle-dependent capillary pressure and relative permeability behavior for the sandstone were evaluated during the experimental program. Relative permeability experiments conducted on samples of the rock included two-phase, unsteady-state, oil-water tests; steady-state, oil-water and gas-water tests; and three-phase, (oil-water-gas) steady-state tests. Electrical resistivity characteristics were measured during the steady-state relative permeability tests.

Hysteresis was evident in the results from each multiple-cycle capillary pressure experiment. The primary effect of cycle-dependent capillary pressure changes for these samples was a reduction in the wettability index with successive drainage and imbibition cycles. Fluid distributions during centrifuge tests, measured using CT scanning, were nonuniform except for saturations near the residual oil or water conditions. Discernable hysteresis effects in the two-phase relative permeability results essentially were limited to the nonwetting-phase relative permeability versus saturation curves between the first drainage and imbibition tests. Wetting-phase relative permeability characteristics were consistent throughout.

Mercury intrusion porosimetry proved effective in developing pore throat size distributions that included information on pores in the submicron range. This information is useful for discerning differences in microporosities between different rock samples.

Maximum capillary pressures induced during centrifuge capillary pressure tests should be limited to values similar to those occurring in the dynamic displacement process in order to yield representative capillary pressure/saturation and wettability information. The use of more than one capillary pressure model is preferred to ensure data interpretation is correct.

Conducting both steady- and unsteady-state relative permeability experiments enables the determination of trends and cross-checking of results. Nonwetting-phase relative permeability values from unsteady-state tests were higher than those for steady-state tests at equivalent saturations. This may suggest higher recovery at water breakthrough if relative permeabilities are calculated from unsteady-state tests for use in prediction of secondary recovery in high permeability rock, such as the Berea sandstone.

Hysteresis in water relative permeability values was not significant for strongly water-wet rock. Hysteresis in oil relative permeability values from oil-water tests was not significant at high oil saturations. Thus, prediction of secondary recovery performance for strongly water-wet rocks should not be significantly affected by hysteresis at high oil saturations. The similarity of water relative permeability values from both oil-water and gas-water tests and the similarity of oil and gas relative permeabilities from oil-water and gas-water tests are indicative of a strongly water-wet system.

Process Utilization and Technology Transfer

A scientist with JAPEX (Japan), who was at NIPER for training during FY90, assisted in this project and coauthored a paper presented at the Society of Core Analysts meeting in Dallas, and a scientist with INTEVEP (Venezuela) developed computer programs for analyzing laboratory relative permeability and capillary pressure data during his tenure at NIPER as part of a training program sponsored by INTEVEP and the DOE. Many projects were undertaken for various major domestic and international oil companies using the knowledge gained and the technology developed as part of this project. These industrial projects were proprietary; however, the breadth of the work included: investigation of the behavior of retrograde gas condensate reservoirs, determination of the best resin-coated gravel for a particular reservoir, measurement of gas-water relative permeabilities and resistivity characteristics of reservoir rock core plugs at ambient and reservoir stress and temperature conditions, and measurement of crude oil-water relative permeabilities for reservoir rock core plugs at reservoir stress and temperature conditions.

Publications

Relative Permeabilities and Other Characteristics of 700-Millidarcy, Fired Berea Sandstone, by D.R. Maloney, A.D. Brinkmeyer, and M.M. Honarpour. Dept. of Energy Report No. NIPER-496, 1990. Available from DOE Bartlesville Project Office, Bartlesville, OK.

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Relative Permeability Technology and Applications, by M.M. Honarpour and D.R. Maloney. Pres. at the Fourth Society of Core Analysts Meeting, Dallas, TX, August 15-16, 1990. SCA paper 9008.

IMAGING TECHNIQUES APPLIED TO THE STUDY OF FLUIDS IN POROUS MEDIA

Principal Investigator:	Liviu Tomutsa
BPO Project Manager:	Robert E. Lemmon
Contract No:	DE-FC22-83FE60149, Project BE12
Funding for FY90:	$391,000 (AEPT)
Period of Performance:	October 1, 1989 – September 30, 1990

Objective

The objectives of this project in FY90 were to develop and use new imaging techniques for measurements of pore geometries and fluid distributions in reservoir rocks at scales varying from a pore to a whole core and to study the effect of small-scale heterogeneities on oil trapping in core-size rock samples. Methods to recover oil can be improved through a detailed understanding of the structure of the rock in a petroleum reservoir since the pore-space geometry strongly influences water, oil, and gas distribution; oil entrapment; and fluid flow properties.

Research Summary

NIPER has developed techniques to make pore-level measurements using computer-assisted image analysis of thin sections and micromodels and through the use of nuclear magnetic resonance imaging (NMRI) microscopy. Also, techniques have been developed for core-scale measurements of heterogeneities and fluid saturation distributions using computed tomography (CT) scanning and NMRI. These techniques enable the examination of rock features and fluid flow at resolutions ranging from 25 to 1,000 μm.

During FY90, the dynamics of fluid flow and trapping phenomena in porous media were investigated using the rock-fluid imaging techniques described below. Miscible and immiscible displacement experiments in heterogeneous Berea and Shannon sandstones were monitored using CT scanning to determine the effect of heterogeneities on fluid flow and trapping. Statistical analysis of pore and pore-throat sizes in thin sections cut from these sandstones enabled the delineation of small-scale spatial distributions of porosity and permeability. Multiphase displacement experiments were conducted using micromodels constructed using thin slabs of the two sandstones. The combination of CT scanning, thin section analysis, and micromodel studies enables the investigation of the influence of variations in pore characteristics on fluid front advancement, fluid distributions, and fluid trapping – phenomena that have a profound effect on the effectiveness of oil production methods.

The CT scans have shown that when capillary forces dominate, i.e., at very low flow rates, heterogeneities in Berea and Shannon sandstones have a more pronounced effect on the oil saturation distribution, after initial oil flooding of the brine saturated rock, than on residual oil saturation distribution after waterflooding. In water-wet systems, capillary forces will tend to hold water in smaller pores forcing oil into higher permeability regions that are swept by injected water. Layers with moderate permeability contrast across the direction of flow reduce the front instabilities and result in piston-like displacement, while permeability layering along the direction of flow contributes to fingering and early breakthrough.

Plugs cut from the two sandstones were investigated using high resolution NMRI, which permitted the visualization of oil, water, or both within individual pores. Newly developed hardware and software permitted the generation of NMRI images with spatial resolutions as low as 120 μm in rock and 25 μm in beadpacks. Figure 6 shows a high resolution image of water in a beadpack having a diameter of 2.7 μm. The brighter areas represent the water filled pores while the dark areas represent the microspheres in the 300 to 500 μm diameter range. The integration of results at different scales using these imaging techniques will advance the understanding as to how small-scale rock heterogeneities influence the behavior of fluids in porous media. The application of these insights will aid in the proper interpretation of relative permeability, capillary pressure, and electrical resistivity data obtained from whole-core studies.

Average saturations during waterfloods of Shannon sandstone, calculated volumetrically and from CT scans, agreed at the 95% confidence level. Average porosities measured using petrographic image analysis of thin sections and routine core analysis of Berea and Shannon sandstones agreed within 1.6 and 4.4%, respectively. Average permeabilities calculated from CT images and routine core analysis for Berea and Shannon sandstones agreed within 2.0 and 9.1%, respectively. Based on CT images, Shannon sandstone is more heterogeneous than Berea with the Shannon having greater porosity and permeability contrasts. Figures 7 and 8 show the differences in flow and trapping characteristics between Shannon and Berea sandstones.

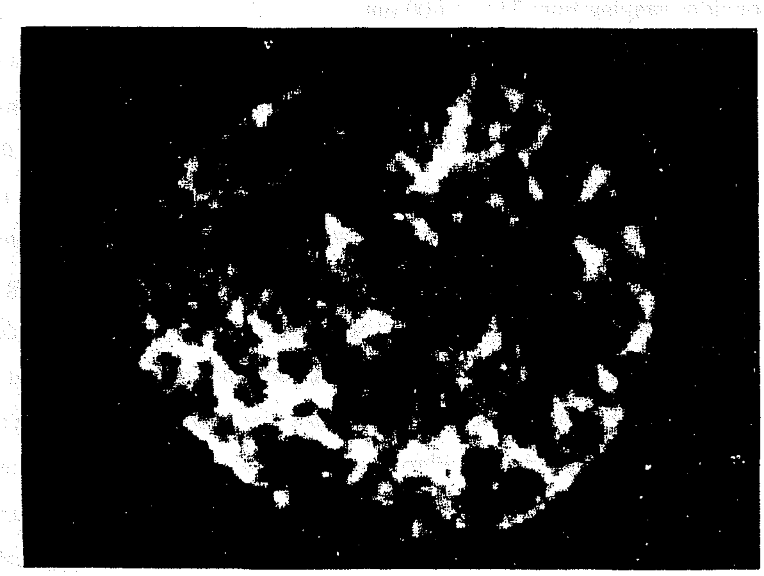

FIGURE 6. - High resolution NMRI image of water saturated beadpack.

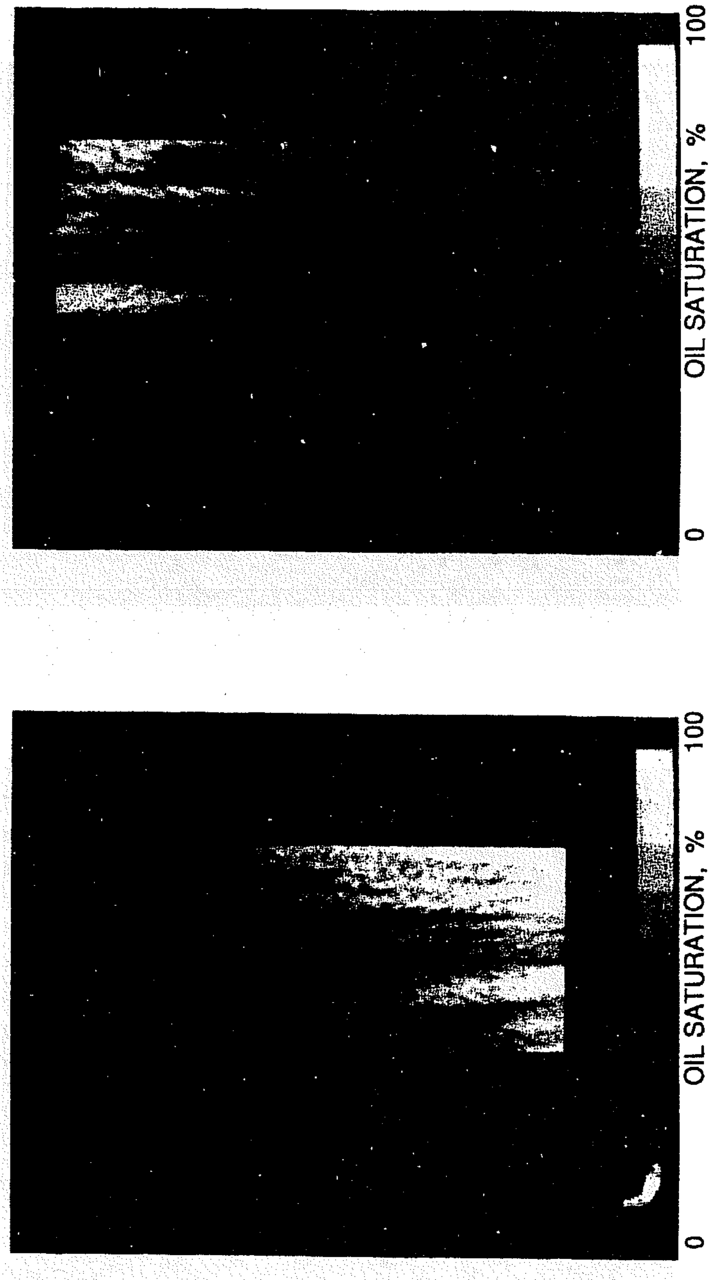

FIGURE 7. - Saturation distributions during (a) drainage and (b) imbibition process in a layered Shannon sandstone slab.

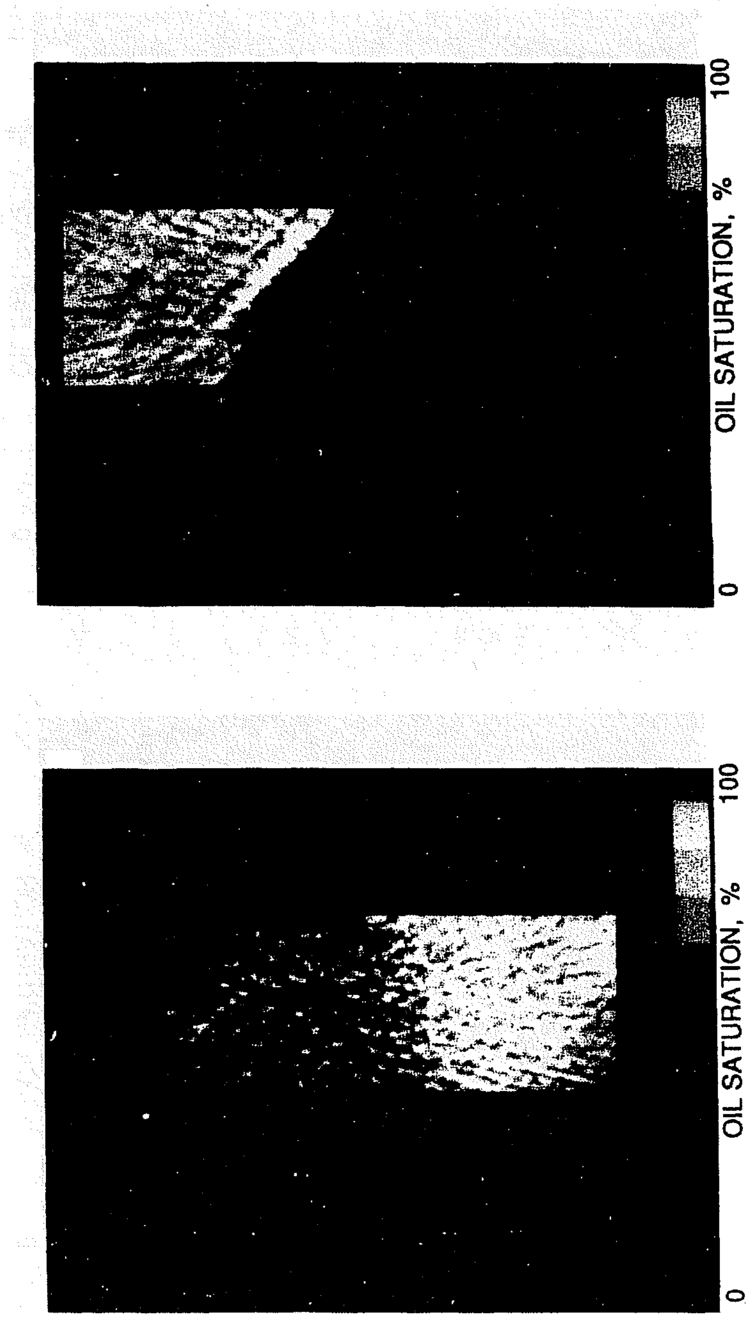

Figure 8. - Saturation distributions during (a) drainage and (b) imbibition process in a laminated Berea sandstone slab.

Process Utilization and Technology Transfer

The knowledge gained and the technology developed in this project are applicable in the near term. Rock and rock-fluid imaging are currently being used at NIPER for industrial clients to select core plug locations and to solve real formation damage and production problems. In addition, rock-fluid imaging is supporting research in other areas such as characterization of pore structures and surfaces, rock-fluid interactions, and residual oil saturation distributions in alkaline-surfactant-polymer flooding.

Almost all of the projects that NIPER conducts for industrial clients in the area of special core analysis involve rock-fluid imaging to some extent. Cores received from the field are scanned using CT to determine their condition and to decide on the location and the number of core plugs required to characterize the core adequately. Other Base Program projects make use of the imaging capabilities to determine the type and degree of heterogeneity of reservoir cores, the behavior of fluids in porous media, and the effectiveness of different EOR methods.

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